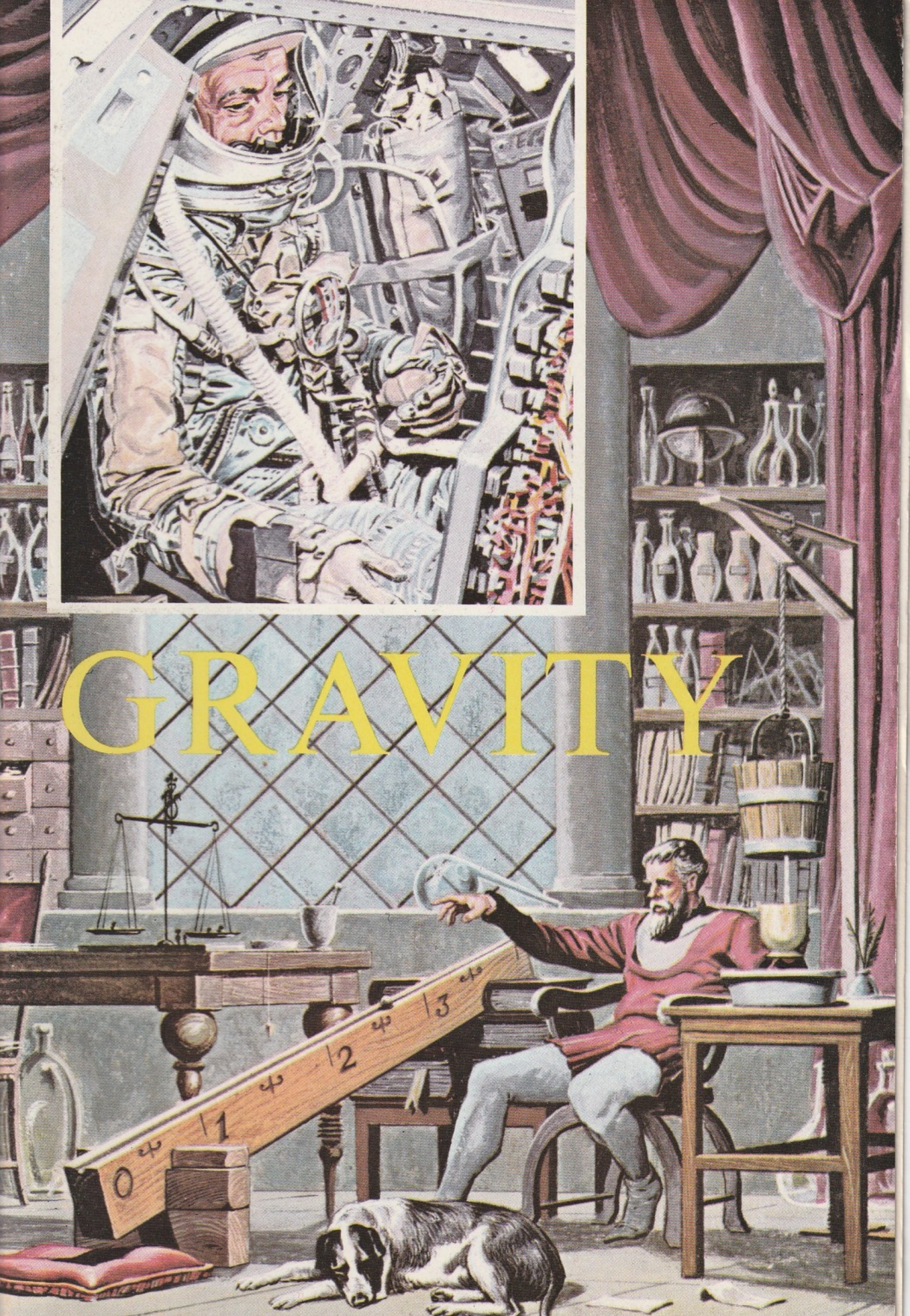
GRAVITY



SCIENCE SERVICE SCIENCE PROGRAM

GRAVITY

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Gravity—an Eternal Mystery

THROUGH THE AGES ancient man looked to the glittering skies and wondered what made the heavens revolve. Were the distant stars really the eyes of gods who roamed daily across their celestial kingdoms? Did magic spirits pilot brilliant jewel-studded ships over cosmic rivers? And later, when down-to-earth science replaced mythological fancy, man asked: "Why do the stars and planets not plummet to earth like an apple from a tree?"

Man has known the answer to this universal mystery for a little less than three hundred years. It was Sir Isaac Newton, the English scientist, who showed that the force that causes the apple to fall toward the ground extends into limitless space and is the same force that causes the moon to make a monthly journey around the earth and causes the planets and comets to circle the sun. This same force, gravity, is something which all objects have, although no one yet knows its cause. We know only that gravity is the force that holds the universe together.

In establishing the Law of Universal Gravitation, Sir Isaac rescued the scientific community from a bitter dilemma. For nearly two thousand years scientists had embraced the erroneous explanation of celestial motion laid down by the great Greek philosopher Aristotle (384–322 B.C.). Although wrong, so logical were the arguments on which Aristotle based his system of physics that they gripped the minds of men in a fierce stranglehold for nearly two millennia.

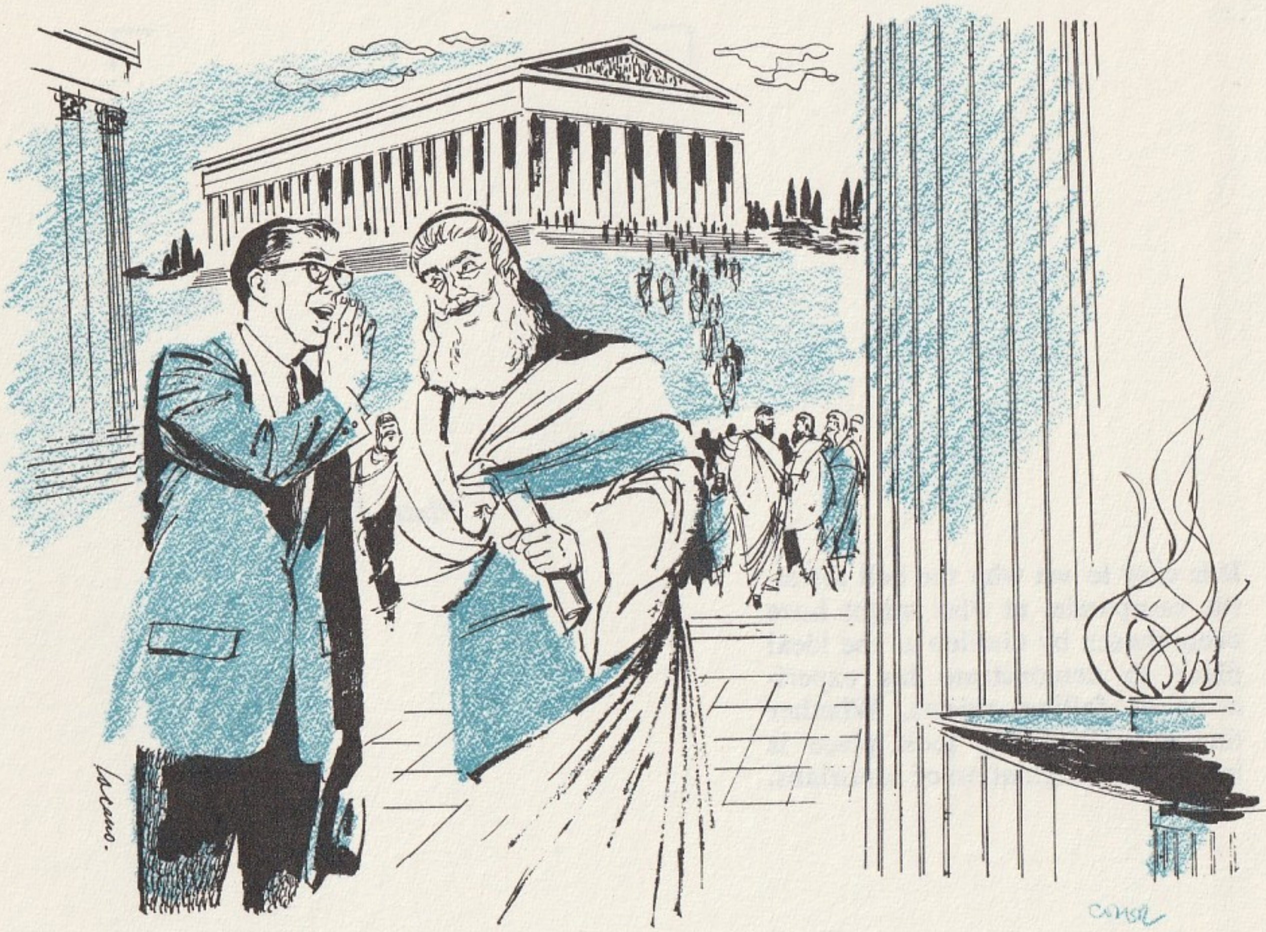
A sky full of mystery.

It is easy to see why the bell tower, the campanile, at Pisa might have been chosen by Galileo as the ideal place to demonstrate his experiment of falling objects. Whether this event actually took place is left to the imagination of historians.

1. LEANING TOWER OF PISA

Gradually, however, toward the end of the sixteenth century, immense cracks began to appear in the scientific structure erected by the Greek thinker. Astronomers such as Copernicus and Kepler turned up evidence which cast serious doubts on the validity of Aristotle's ideas. Like most people, scientists don't like to have the rug pulled out from under them, especially a rug which had faithfully served the scientific brotherhood for so many hundreds of years. Some scientists who recognized that the Aristotelian view of the universe—so long taken for granted—was in great jeopardy and not likely to survive the onslaught of mounting scientific data opposing it, scurried about in a final effort to find new arguments with which to patch up the chinks in the old system.

It was to no avail, for it finally came to pass at the beginning of the seventeenth century that the Italian scientist Galileo exploded the Aris-



totelian system forever, with a few simple experiments. Thereupon, to explain the mechanics of the universe, a new system had to be constructed. Sir Isaac Newton was the master builder who drew up the blueprints.

As Aristotle Saw Things

If Aristotle was wrong, why did it take two thousand years to demolish his views? Perhaps if we pay a visit to ancient Greece, at one time the center of learning, we might better understand what kept scientists from making any progress in this field.

Imagine that you are a modern twentieth-century scientist—transported back in time to the year 350 B.C. You march down a street in Athens. Along comes a dignified gentleman sporting a long beard, a flowing white robe and a twinkling smile. He is Aristotle. Seeing that you are a stranger, he stops to say hello. You cast your eyes to the sky and begin speaking of the universe.

On Earth As It Is in the Heavens

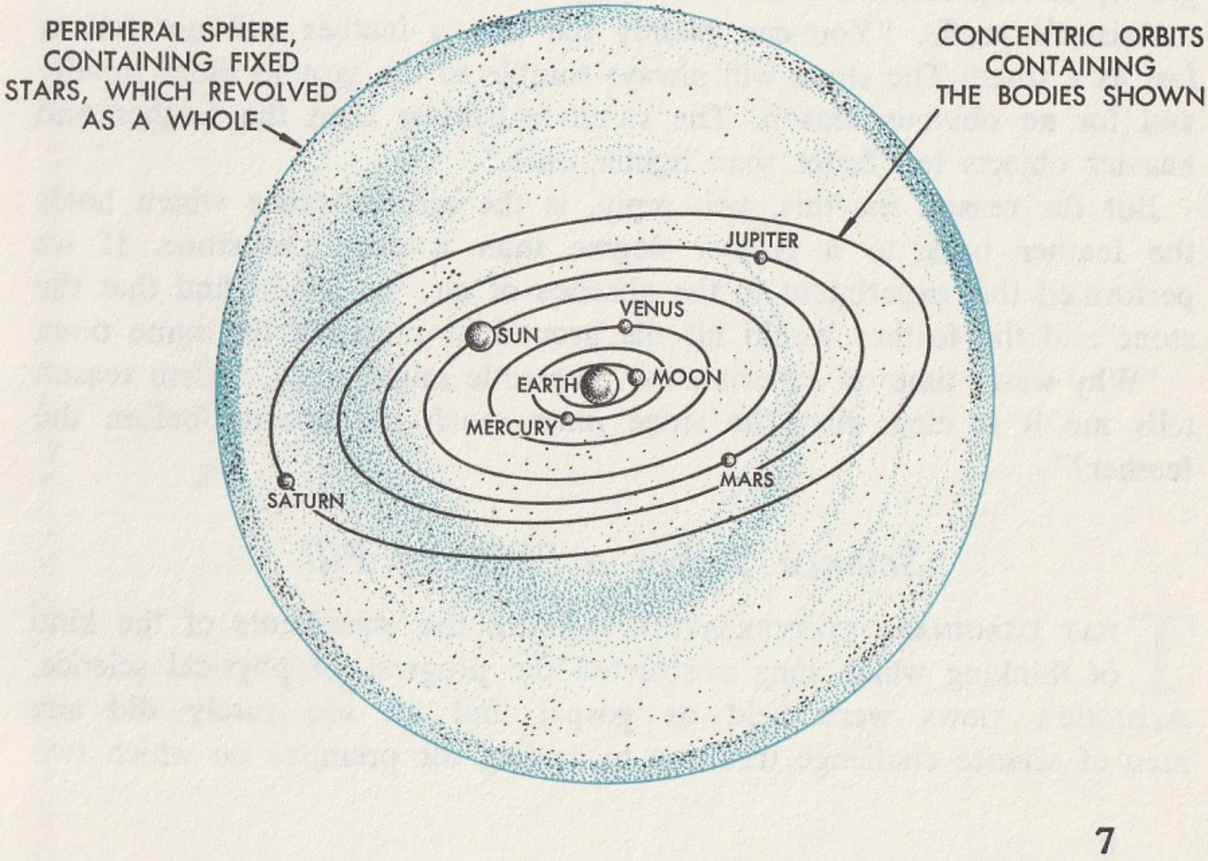
"Isn't it amazing," you begin, "that the great, mysterious force which guides the destinies of the planets and stars is the same force which causes objects to fall to the ground?"

Gravity is everywhere, you tell Aristotle, on earth as it is in the heavens. Every object large or small—from a tiny pea to the largest star—exerts a gravitational pull. Gravity is a characteristic of all matter. Everything attracts everything else, some things more than others, of course. The more matter there is, the greater the gravitational attraction between objects. Gravity keeps the earth revolving around the sun.

"No, no, no," Aristotle replies, "you're quite wrong."

The truth of the matter, he insists, is that the heavenly bodies are all lodged in invisible spheres. It is these spheres which revolve around the earth. The earth is completely stationary and is at the exact mid-point of the universe, like the hub of a wheel about which all else turns. There are fifty-five concentric spheres, all told. So says Aristotle.

ARISTOTLE'S CONCEPT OF THE UNIVERSE—FINITE IN ALL RESPECTS



You sit down under a tree, munch a few figs and continue your conversation. "What makes the heavenly spheres revolve?" you ask.

"It is *natural* for them to move in circles," Aristotle replies.

He tells you that there are two kinds of natural motion—motion in a straight line and circular motion. Straight-line motion is the *natural* motion for objects on the earth. The perfect motion—circular motion—is natural for the perfect bodies of the universe. Thus, the spheres revolve carrying the heavenly bodies with them.

"You have noticed, of course," Aristotle says, "that when a fig falls from a fig tree it drops to the ground in a straight line. All objects on the earth seek their natural place. And what is that natural place? It is the central point of the universe—the exact middle of the earth!"

The Feather and the Stone

YOU TRY ANOTHER TACK. This time you tell him that you have heard of some of his other notions concerning falling objects. You recall his assertion that heavy bodies fall to the ground faster than light objects if they are dropped from the same height at the same time. You tell him that this is false. You explain that all objects, heavy or light, are accelerated at the same rate—they fall faster and faster and side by side; gravity is responsible for making them accelerate toward the earth.

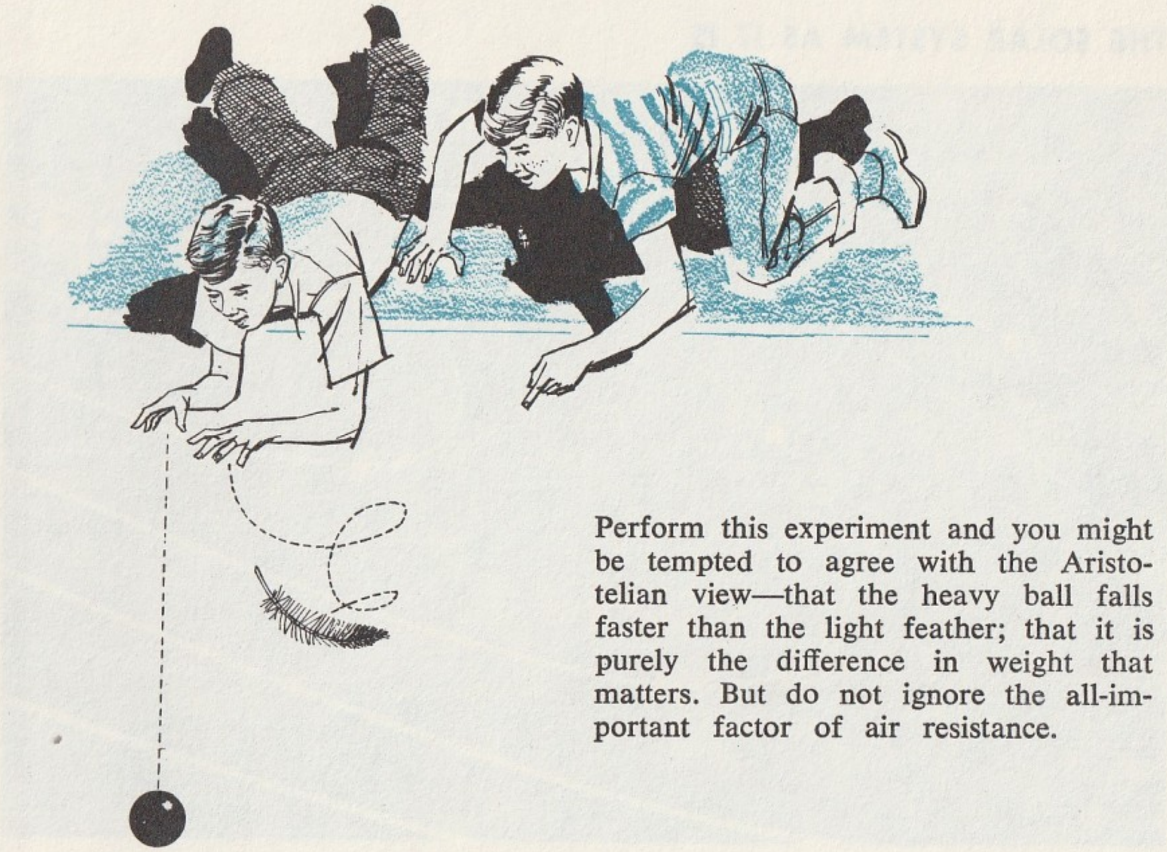
Aristotle scoffs. "You can plainly see that a feather will not fall as fast as a stone. The stone will always tumble to the ground more rapidly and for an obvious reason. The stone is heavier than the feather and heavier objects fall faster than lighter ones."

But the reason for this, you reply, is the air resistance which holds the feather back to a greater degree than it does the stone. If we performed this experiment in the absence of air, we would find that the stone and the feather would hit the ground at precisely the same time.

"Why waste time on experiments," Aristotle might reply, "when reason tells me it is clear that the stone *must* reach the ground before the feather?"

Science Takes a Sleeping Pill

THAT IMAGINARY CONVERSATION contains the ingredients of the kind of thinking which long obstructed the progress of physical science. Aristotle's views were held as gospel and all too rarely did any man of science challenge tradition by testing the premises on which two



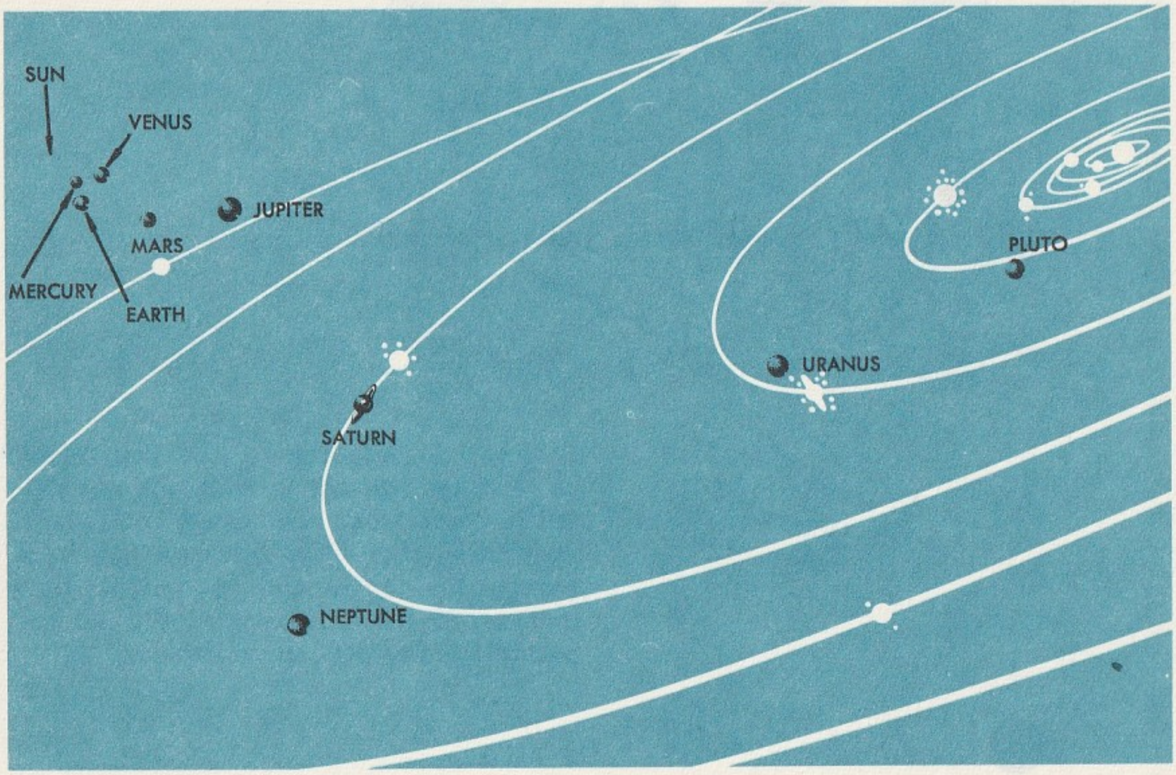
Perform this experiment and you might be tempted to agree with the Aristotelian view—that the heavy ball falls faster than the light feather; that it is purely the difference in weight that matters. But do not ignore the all-important factor of air resistance.

thousand years of science were built. Generally, experiments were disdained as irrelevant. Scientists following in the wake of Aristotle were content to work under the delusion that pure scientific knowledge was gained merely by reasoning. They were armchair detectives who believed they could solve the mysteries of the universe by allowing their thoughts to knit a few scattered observations into a general truth. "Anyway," they may have said, "Aristotle has supplied all the answers and all is well with the universe."

But all was far from well. In 1530, a fifty-seven-year-old Polish canon trained in astronomy, Nicolaus Copernicus, started the rumblings which were to loosen this scientific logjam.

A deeply religious man, Copernicus felt that the central-earth (or geocentric) system of the universe as taught by Aristotle, and as subsequently modified and catalogued by the astronomer, Ptolemy of Alexandria, in Egypt in the second century, was far too complicated. Copernicus trusted that the Lord should have made a simple universe and not one as elaborate and almost incomprehensible as that demonstrated by Ptolemy

THE SOLAR SYSTEM AS IT IS



in his famous treatise on astronomy, *The Almagest.* Copernicus made a thorough study of the rotation of the planets in our solar system. As a result of his investigations, he formed a startling theory: the sun, not the earth, was the central object of the solar system. And the earth and the other planets were in motion, rotating in circular orbits around this fiery ball.

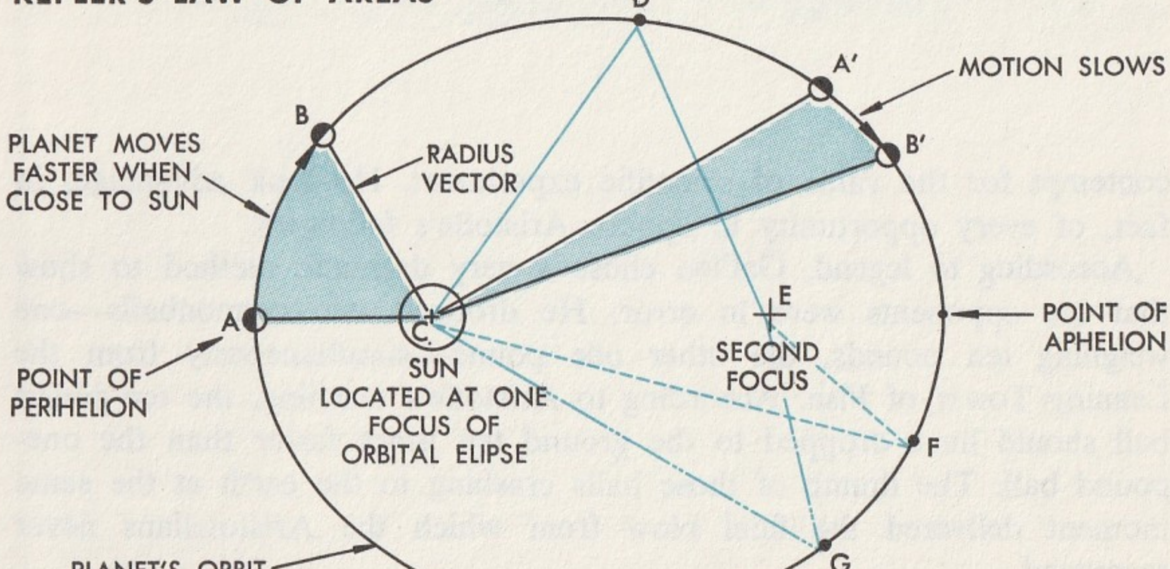
The Aristotelian system, remember, was based on the belief that the earth was stationary, as well as central. Now that the earth had been dislodged from its position at the middle of the universe and was reputed to move, wouldn't this discredit the whole Aristotelian scheme? In time it would, but the geocentric system had been cherished for thousands of years. Copernicus knew people are often very reluctant to discard ideas which they have for long believed to be true. Fearing repercussions if he made his findings public, Copernicus waited thirteen years to publish his revolutionary "central sun" (or heliocentric) theory. He died about the time of publication.

In 1609, the German astronomer Johannes Kepler dropped another hot potato into the lap of Aristotelian dogmatists. He discovered that the orbits traced by the planets around the sun were not pure circles at all. Rather they were ellipses, or stretched-out circles. Another of the bricks with which the old school of physics had been built was sent toppling. The pure circle, the aristocrat of geometric figures so dear to the Aristotelians, was not the characteristic motion of the heavenly bodies.

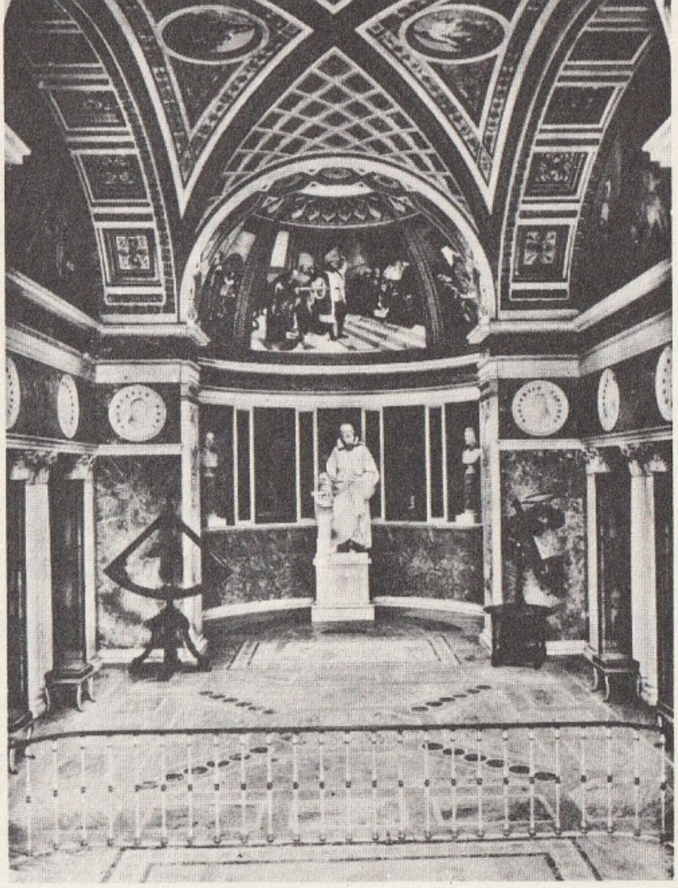
Galileo's Cannonballs

THE HELIOCENTRIC THEORY OF COPERNICUS drew the brilliant Italian scientist Galileo (1564–1642) as an ardent supporter. He was also a fervent critic of Aristotelian science, which he was determined to displace from its top-ranking position. He challenged openly the old camp's

KEPLER'S LAW OF AREAS



In a true ellipse the distance from C to D to E=C to F to E=C to G to E. It is also equal to the longest axis of the ellipse. This relationship holds for every point on the ellipse. Kepler's law of areas states that a body moves around an elliptical orbit in such a way that the radius vector sweeps over equal areas in equal intervals of time. Therefore area A-B-C=A^1-B^1-C and the time required to move from A to B equals that required to move from A^1 to B^1. This is why satellites orbiting the earth travel faster at perigee than at apogee.



The Tribune of Galileo at the Museum of Natural History, in Florence, Italy.

contempt for the value of scientific experiment. He took advantage, in fact, of every opportunity to oppose Aristotle's followers.

According to legend, Galileo chose a very dramatic method to show that his opponents were in error. He dropped two cannonballs—one weighing ten pounds, the other one pound—simultaneously from the Leaning Tower of Pisa. According to Aristotle's teaching, the ten-pound ball should have dropped to the ground ten times faster than the one-pound ball. The thump of those balls crashing to the earth at the same moment delivered the final blow from which the Aristotelians never recovered.

While historians are in dispute as to whether Galileo actually performed this experiment, it might well stand as a symbol signifying the birth of experimental science and the demise of Aristotelian science.

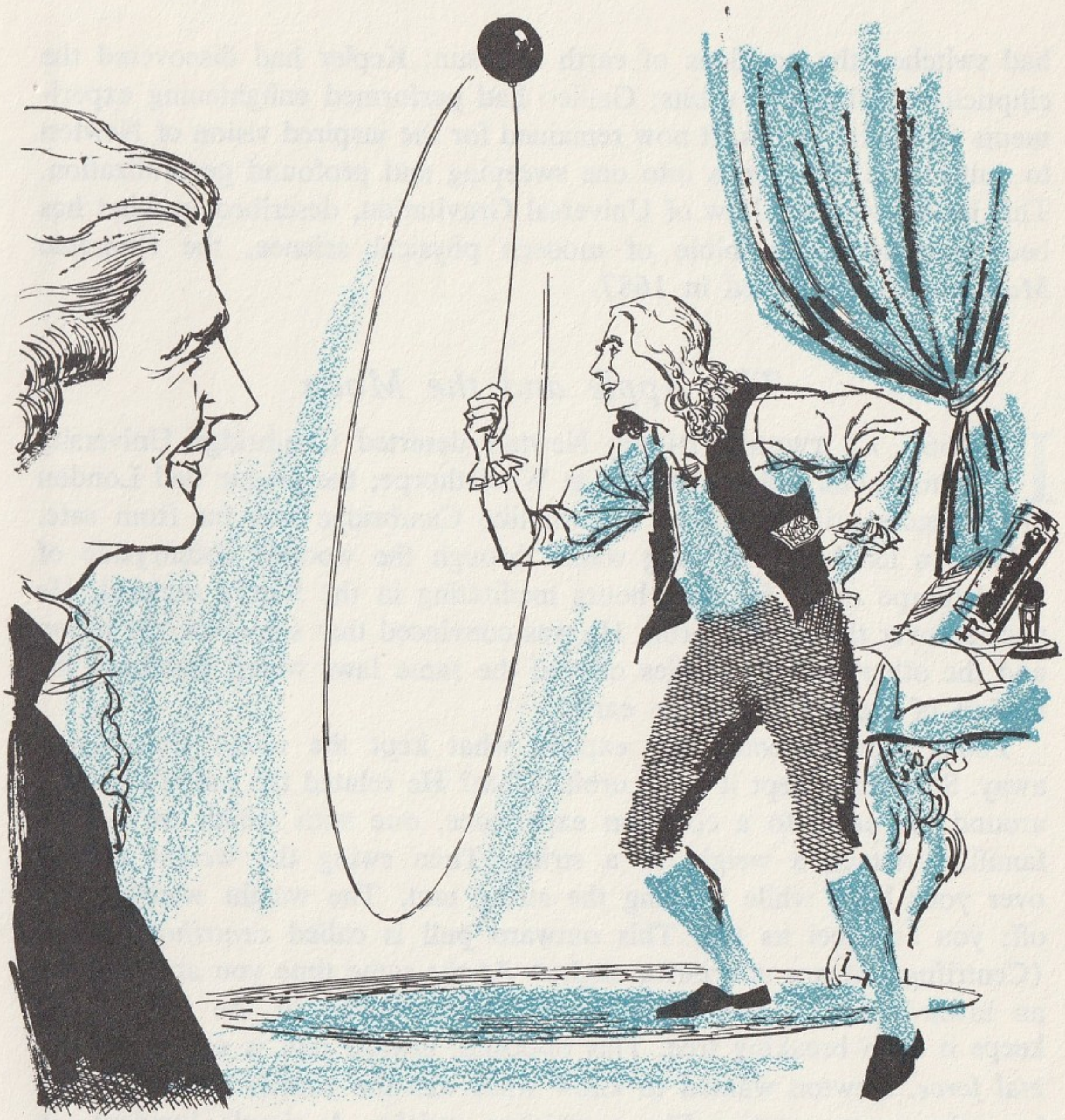
Eager to pursue his investigation of the motion of falling bodies, Galileo devised a more detailed experiment. He rolled balls down measured slopes which were sufficiently gradual for the balls to roll slowly enough to be timed. By making his inclines steeper and steeper he was able to approach vertical or free fall. On the basis of these observations and


Lacano

calculations, he concluded that free-falling bodies drop with constant acceleration toward the earth. No matter what the weight, the acceleration is always the same—about thirty-two feet per second per second. This means that a body starting from rest would, in absence of air resistance, attain a speed of thirty-two feet per second (21.8 miles per hour) after one second of free fall, sixty-four feet per second (43.6 miles per hour) after two seconds, ninety-six feet per second (65.5 miles per hour) after three seconds, and so on.

2. PARACHUTE JUMPERS PREPARE TO TAKE OFF

The sport of sky-diving—parachuting—is relatively new. Gravity, of course, plays a vital role. Without it the parachutist would never come down! The chute itself counteracts some of the force of gravity by adding wind resistance, thereby slowing the rate of descent.



Newton—the Master Scientist

SIR ISAAC NEWTON WAS ONCE QUOTED as saying: "If I have seen further than others, it is by standing on the shoulders of giants." No doubt the master scientist was referring particularly to Copernicus, Kepler and Galileo. Indeed, they had laid the groundwork and supplied the new bricks from which Newton was able to erect a new system of mechanics to replace the demolished ruins of the Aristotelian school. Copernicus

had switched the positions of earth and sun; Kepler had discovered the ellipticity of planetary orbits; Galileo had performed enlightening experiments on falling bodies. It now remained for the inspired vision of Newton to unite these discoveries into one sweeping and profound generalization. This he did with his Law of Universal Gravitation, described in what has been considered the bible of modern physical science, the *Principia Mathematica,* published in 1687.

The Apple and the Moon

IN 1665, AT TWENTY-THREE, Newton deserted Cambridge University for his countryside birthplace at Woolsthorpe; the plague had London in its deadly grip, and even a town like Cambridge was far from safe.

Newton liked to take long walks through the wooded countryside of Woolsthorpe or sit for long hours meditating in the family orchard. He puzzled over the moon's orbit. He was convinced that somehow the moon and the other celestial bodies obeyed the same laws which governed the motion of moving bodies on earth.

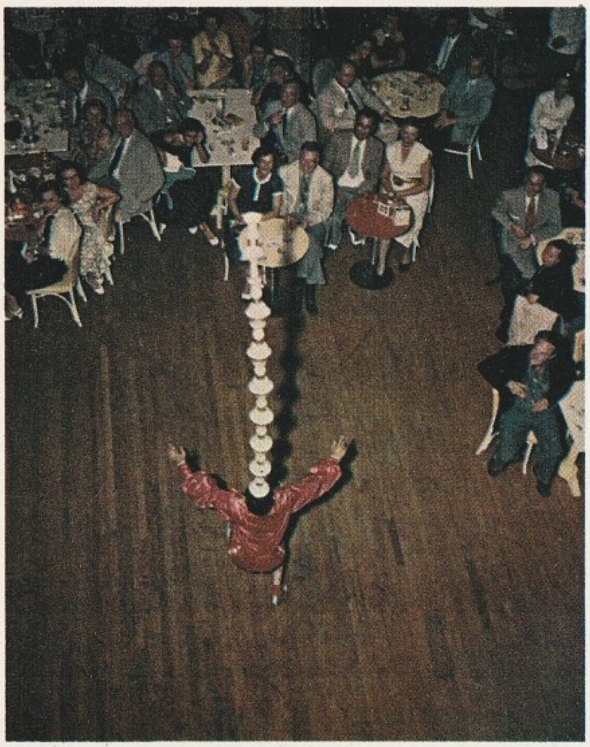
Young Newton could not explain what kept the moon from flying away. Something kept it in its orbit. What? He related the moon's motion around the earth to a common experience, one with which we are all familiar. Attach a weight to a string. Then swing the weight around over your head while keeping the string taut. The weight wants to fly off; you can feel its tug. This outward pull is called *centrifugal force.* (Centrifugal means anticentral flight.) At the same time you are applying an inward pull to the string which is transferred to the weight and keeps it from breaking free. This opposite, inward pull is called *centripetal force.* Newton wanted to know what was the cosmic "string" which kept the moon rotating like a whirling weight. A simple incident—it, too, legendary—helped Newton find the answer; one autumn day an apple fell to the grass near the master scientist as he sat under a tree in the family orchard. The thought came to him: "Is it not possible that the same force which pulls the apple down is also the 'string' which pulls the moon out of the straight-line course and keeps it cart-wheeling around the earth on its twenty-seven-day circuit?"

He pressed further. Why couldn't this force which caused the apple to fall extend beyond the tallest mountains and into space? No doubt the force diminished as the distance from the earth increased, but exactly how weak would the force be by the time it reached the moon?

The Inverse Square Law

NEWTON REASONED THAT the gravitational pull exerted by the earth (or any other object, for that matter) must decrease very rapidly with distance. Precisely, the force is *inversely proportional* to the square of the distance from the center of the earth. Doubling the distance would reduce the force of gravity to one-quarter; four times the distance would mean one-sixteenth the force, and so on. This is known as the *Inverse Square Law*.

Balancing acts like this depend on successful distribution of masses about a point that behaves as if *all* the masses involved were concentrated in it. The center of gravity of the combined masses of all the objects must be on a line vertically above the performer's head.



3. BALANCE AND GRAVITY

Returning to Cambridge in 1667, Newton backed up his reasoning by calculating the shape of a gravity-controlled orbit, applying the inverse square principle. His investigation revealed that the planets would "ride" elliptical orbits! So Kepler's work was borne out on theoretical grounds. Here was the universal "string" necessary to keep the moon and the planets in their elliptical orbits. And this was the only force necessary. Gravity was the spoke on which the universe wheeled.

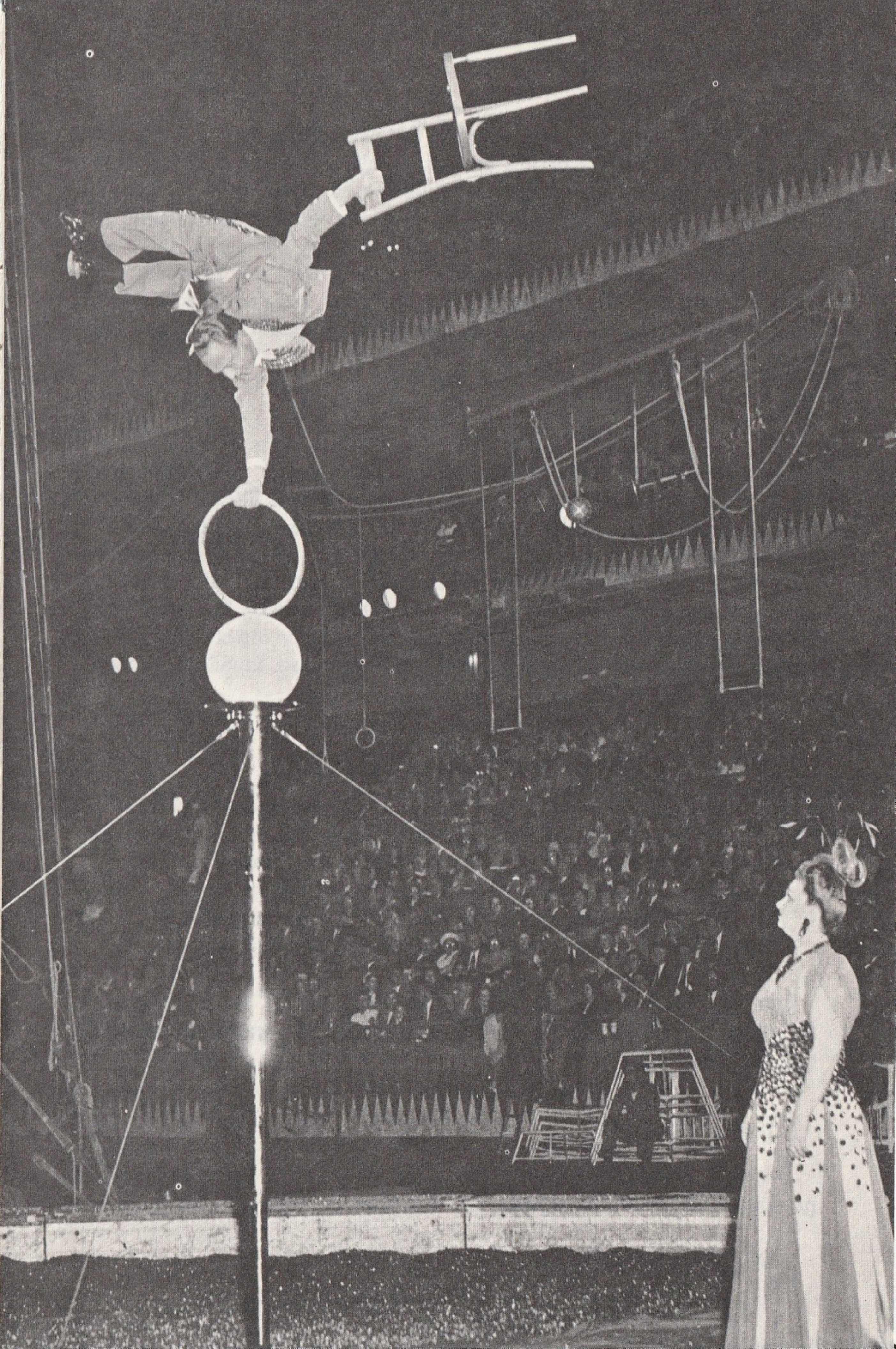
This European hammer thrower swings the hammer around at the greatest speed he can achieve, so that when it is released, it will travel the greatest possible horizontal distance before gravity causes it to reach the ground.

Mass and Weight

NEWTON ALSO DEDUCED that the intensity of the gravitational force depended on still another factor: the mass of an object. He explained that the force of mutual attraction exerted by two bodies was directly proportional to the product of the masses of the pair; the greater the masses the stronger the attraction.

We must make a careful distinction between *mass* and *weight*. The two are often confused. Weight, or heaviness, is the measure of the

(*Right*) In this balancing act the center of gravity is located in a vertical line through the bottom of the hoop.



pull of gravity upon a mass. Suppose, for example, that you weigh 150 pounds. That means the earth's gravity is pulling you down with a force of 150 pounds; and you are also pulling the earth toward *you* with the same force! Now imagine yourself on the moon. Our natural satellite has gravitational strength only about one-sixth that of the earth; there you would weigh about twenty-five pounds, but you would still have the same amount of bone, tissue, muscles and organs. Your mass remains the same. Your weight, however—the pull of gravity upon your mass—may vary from place to place.

Center of Gravity

When we discussed the Inverse Square Law you might have wondered why the force of gravity tapered off with distance measured from the central point in the earth. Newton showed that gravity behaves as if all the mass of an object were concentrated at a single point, the center of gravity. For solids like spheres and cubes, this point is located at the geometrical center. For other "nonregular" objects, the point might be located elsewhere. Try balancing a spoon on your index finger. When you have found the balancing point, you have also found the spoon's center of gravity.

Newton's Famous Equation

We are now ready to use a shorthand expression for Newton's Law of Universal Gravitation. Let us first restate the law verbally (notice the use of the word *proportional,* not *equal to*):

> Every particle attracts every other particle with a force directly proportional to the product of their masses and inversely proportional to the square of the distance between them.

Our last step is to introduce a special factor which makes it possible for us to put an equal sign into our mathematical expression. We shall call this factor *Big G.*

The equation, then, is:

$$F=G\frac{m_1m_2}{r^2}$$

Where F is the gravitational force, m_1 and m_2 are the masses of the particles and r^2 is the square of the distance between the particles.

Powerful and majestic is this equation. With it, for example, scientists have been able to "weigh" the earth (6,000,000,000,000,000,000,000 tons). And astronomers have determined the masses of the other bodies in our solar system including that of the sun.

To put the equation to practical use, however, scientists first had to find a value for Big G. Sir Isaac could only estimate it roughly.

For all of us in this world—except for a few select astronauts—gravity is part of our way of life. To defy it, even accidentally, is to invite bruises or broken bones.

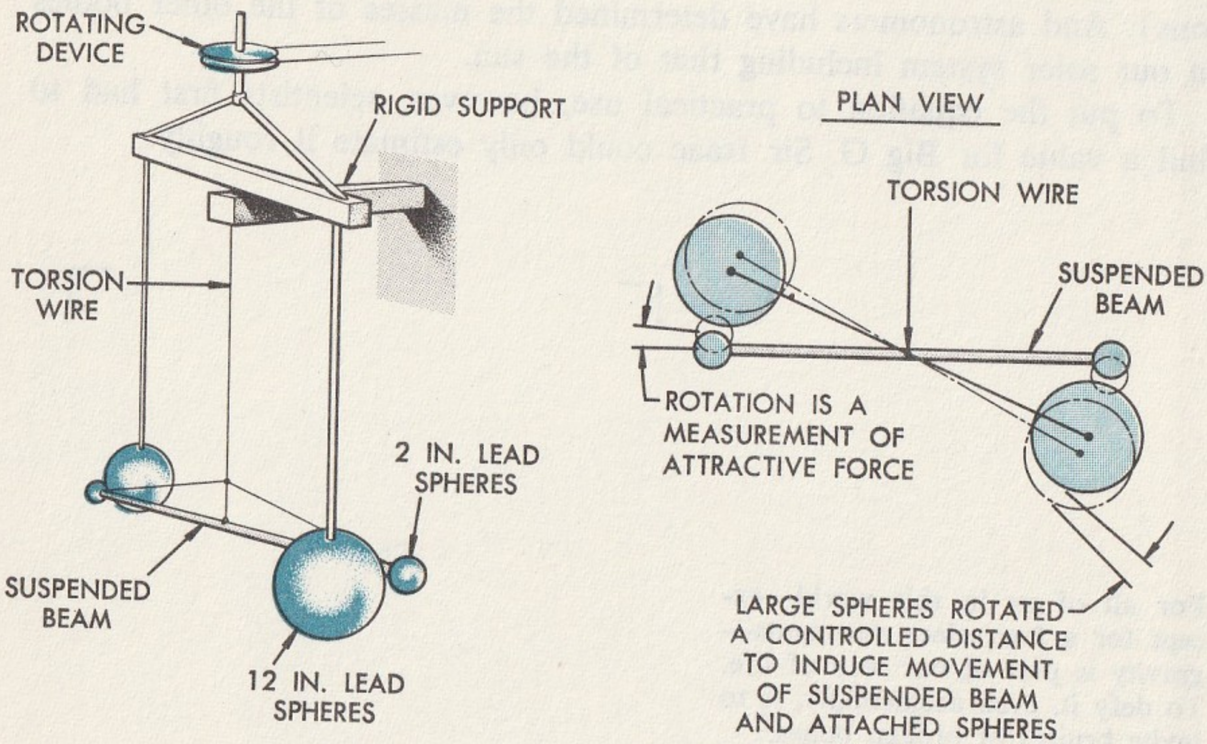
4. HE DEFIED GRAVITY!

Big G—Universal Constant

THE UNIVERSAL GRAVITATIONAL CONSTANT, G, is one of the most important numbers in physics. It is called a universal constant because its value is the same everywhere in the universe. G of the earth and earthly objects is equal to G of the sun. Both exhibit the same G as do the stars billions of light-years away. In this way, Big G is very much like another basic number of immense importance to scientists—*c*, the velocity of light. The value of *c* is the same everywhere in empty space. But where the velocity of light is large (186,000 miles per second), Big G has an incredibly small value. Yet tiny as it is, Big G holds regal rank as a scientific tool.

Let us rearrange Newton's equation by shifting some terms around so that $F = G\frac{m_1m_2}{r^2}$ now becomes $G = \frac{Fr^2}{m_1m_2}$. This tells us that to find the value

TORSION BALANCE USED BY CAVENDISH



of G, we simply need to determine the force of attraction between two known masses separated by a known distance. It sounds easy. But putting it into practice is a very tricky task indeed.

The problem is that, of all the universal forces, gravity is by far the weakest. If we judge from our everyday experience, this might seem to be an unbelievable statement. The bruises and broken limbs that are our rewards when we try to defy gravity could well testify to its great strength. But, as you have no doubt guessed, our sometimes painful awareness of gravity at work stems from the huge mass of the earth which compounds the tiny effects of gravity until they become obvious.

On the other hand, the gravitational attraction between two masses of ordinary size—of a scale, for example, that scientists can handle in a laboratory test—is so small as to be exceedingly hard to measure. It has been determined, however, that two one-pound balls placed a foot apart attract each other with a force of about 0.0000000000005 of an ounce. Obviously, to measure such a fantastically small amount requires exceptionally delicate instruments.

The Cavendish Experiment

ABOUT A HALF CENTURY after Newton's death, an English scientist, the Reverend John Mitchell, devised a simple but ingenious laboratory experiment which was to serve as the basis for a close determination of the value of Big G. Mitchell completed his apparatus in 1798 but died before he could carry out his test. Luckily, his equipment found its way into the hands of another English scientist, Henry Cavendish, the discoverer of hydrogen. Before performing his experiments, Cavendish first redesigned some parts of the equipment.

Paul R. Heyl conducting his famous measurement of the universal constant of gravitation.

The apparatus consisted of two small spheres of known mass attached to either end of a long rod. This dumbbell-type arrangement was suspended from a twistable filament so that the entire contraption formed an upside-down letter T. Cavendish placed large lead balls of known mass on opposite sides of the rod near the smaller spheres. The gravitational pull between the large and small masses caused the rod to swing horizontally. This produced a twisting action which Cavendish was then able to convert into a value for the force of mutual attraction. Then, by simple calculation using the rearranged Newtonian equation, he found his answer for Big G.

The Standard Value of Big G

FOR A LONG TIME Cavendish's value for Big G was accepted as the standard by the scientific community. But new refinements in experimental equipment were steadily being made and more precise determinations of Big G found. In 1942 a scientist at the National Bureau of Standards in Washington, D.C., Dr. Paul R. Heyl, made the most accurate measurement of Big G to that date, using an improved Cavendish-type arrangement which ensured a degree of accuracy impossible with Cavendish's original. Heyl took extensive precautions. He used steel cylinders instead of lead spheres to ensure precise dimensions, masses, densities and distances. He shielded his entire apparatus against the earth's magnetic and electric fields to guard against minor errors. Heyl also used a high-accuracy mirror and telescope system to observe the size of the arc through which the rod swung. From this he obtained the new standard value of G. The value: $G = 6.673 \times 10^{-8}$ or, written out, 0.00000006673 (cubic centimeters per gram per second per second). No need to concern yourself about the units. Just note how minute this number is. Small wonder that the force of gravity is so weak and requires such enormous masses to make its presence felt.

Gravity and the Tides

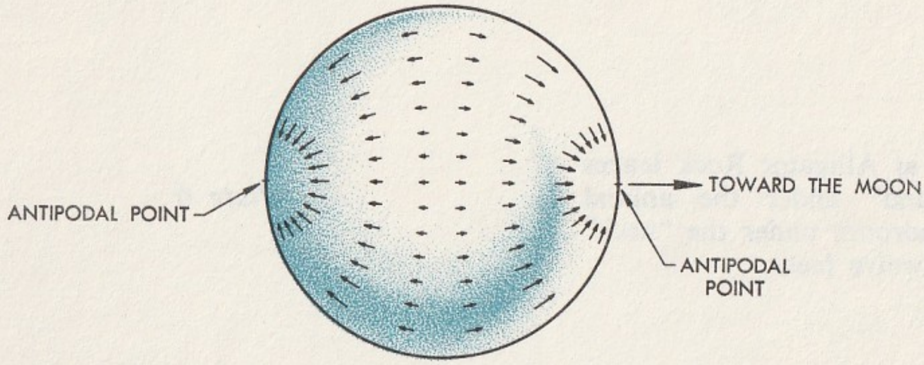
GRAVITY IS A FACT OF LIFE which makes life itself possible. Apart from keeping us "glued" comfortably to our planet—even while the earth races around the sun at a speed of 67,000 miles per hour—gravity keeps a tight rein on our life, holding earth's atmospheric blanket in place. It has been estimated that if the earth's gravitational force had very much less than its actual strength, most of our atmosphere

would have been lost to interplanetary space ages ago; hence the lifelessness of the moon. If it ever did have an atmosphere anything like ours, the moon's weak grasp would not have been able to hold on to energetic, heated air molecules.

While the weatherless atmospheric moon was unable to muster the strength necessary to retain its atmospheric canopy, its gravitational force nevertheless was large enough to produce some startling effects on earth, some quarter of a million miles away.

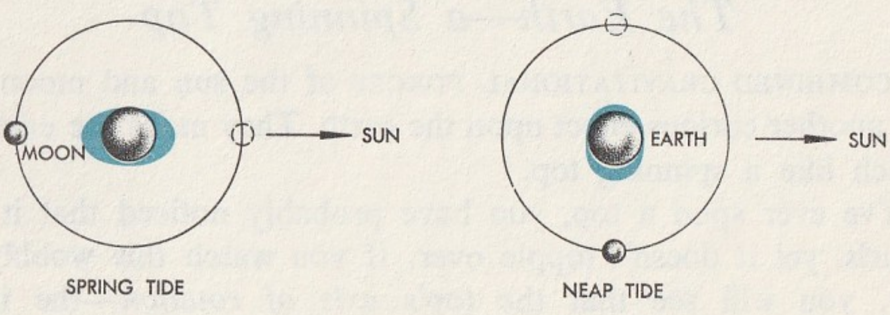
The moon is the principal cause of the earth's regular cycle of high and low tides. The sun has a hand in this phenomenon too, but its role is secondary because of its distance from the earth (93 million miles). Scientists estimate that the sun's effect upon the earth's tides is only two-fifths as strong as that of the moon.

TIDE-PRODUCING FORCES



The system of arrows represents the horizontal components of the moon's tide-producing force. Lengths of the arrows indicate the strength of the force. The forces at the two antipodal points and all points on the great circle midway between them, which bisects the sphere, are zero.

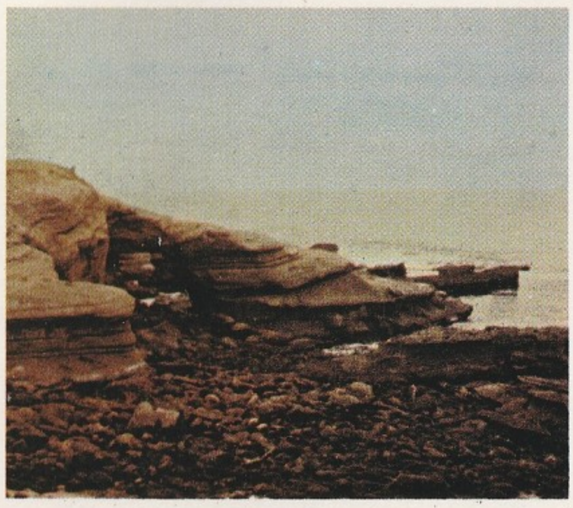
When moon, sun and earth are in line they produce spring tides. Neap tides occur when sun and moon are at right angles to each other.



During high tide at Alligator Rock, La Jolla, California, the sea pounds under the animal's "neck"—once every six hours.

5. HIGH TIDE

Low tide at Alligator Rock leaves the "ground" under the animal bare. Headroom under the "neck" is about twelve feet.



6. LOW TIDE

The Earth—a Spinning Top

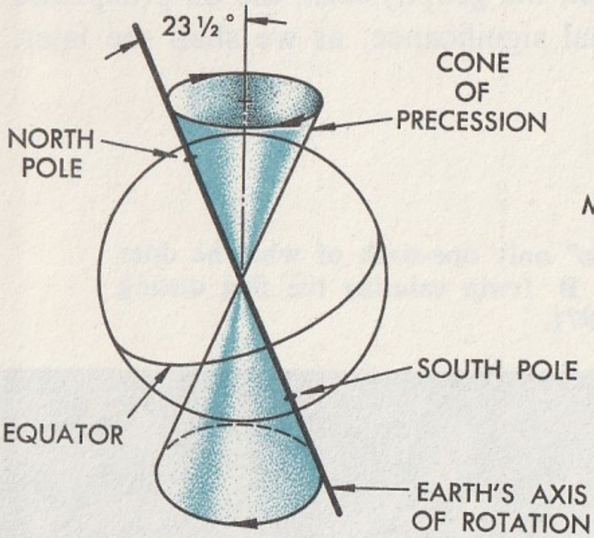
THE COMBINED GRAVITATIONAL FORCES of the sun and moon produce still another curious effect upon the earth. They make the earth behave very much like a spinning top.

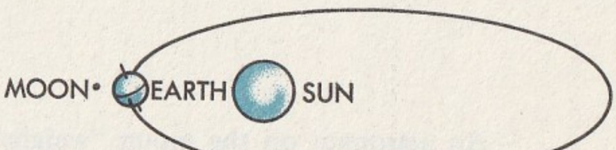
If you've ever spun a top, you have probably noticed that it wobbles as it whirls, yet it doesn't topple over. If you watch this wobbly motion carefully, you will see that the top's *axis of rotation*—the imaginary

line about which it spins—traces out the shape of a cone, whose tip is the point where the top is touching the ground.

In the same way, the axis of rotation about which the earth spins undergoes conical motion even while the earth travels around the sun on its yearly journey. The apex, or tip, of the cone generated by the spin axis lies at the earth's center of gravity. The motion is called *precession.*

PRECESSION OF THE EARTH





It requires 26,000 years for one complete revolution of the earth's axis through its cone of precession—or one complete circuit from the position shown above, all the way around to that point again while the earth continues traveling in orbit.

The earth is not perfectly spherical, but is bulged somewhat around the equator—or flattened towards its poles. It also spins around an axis of rotation which is far from perpendicular to the plane of orbit around the sun.

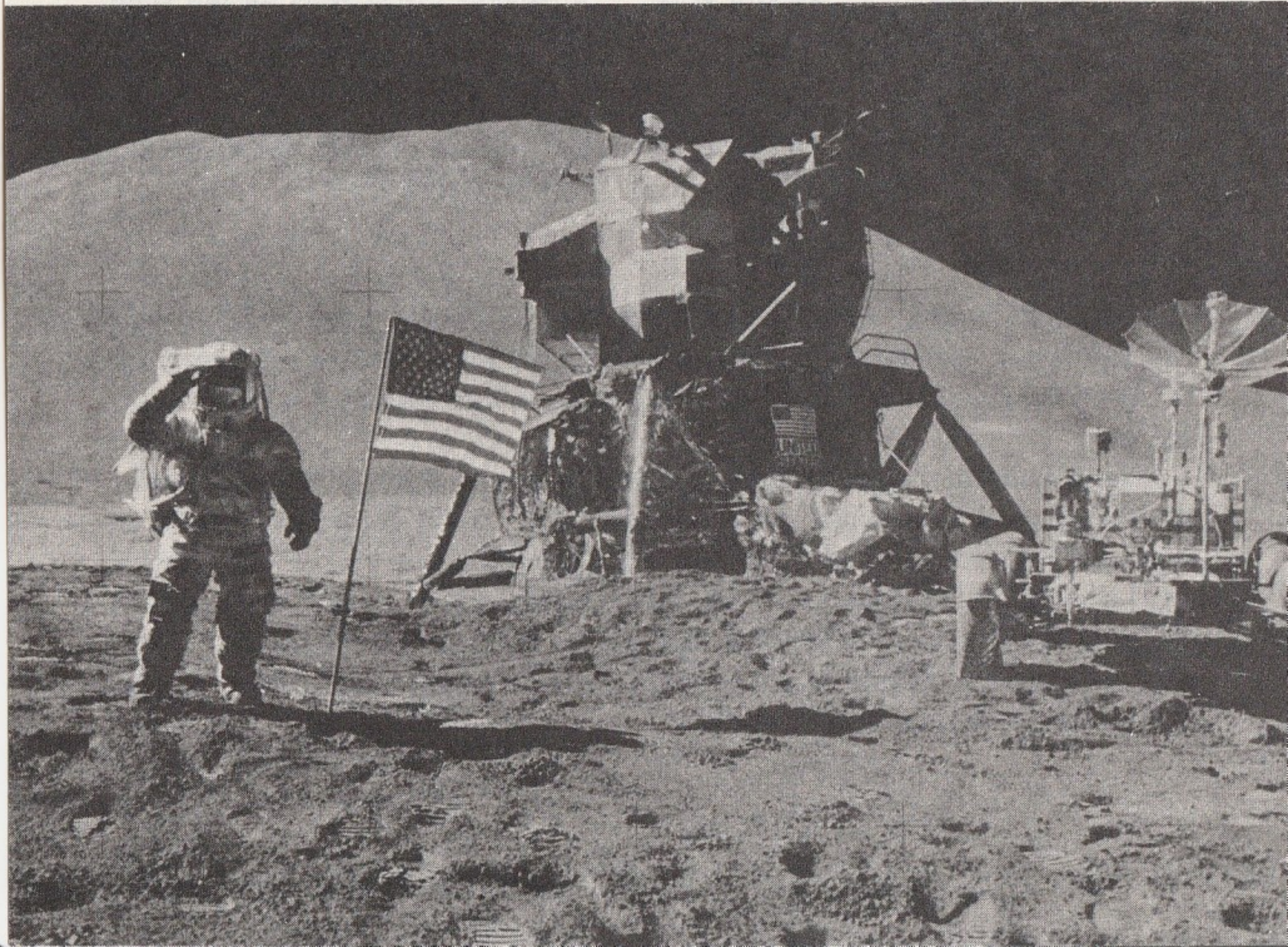
The equatorial bulge behaves just as though it were a ring of matter surrounding and attached to the earth. The sun's force of gravity is continually exerting a pull on this bulge, tending to "leave the earth's axis upright". The moon, on the other hand, exerts a pull which tends to bring the bulge into line with the plane of its own orbit of the earth. The two effects combine to produce the slow conical wobble of the earth's axis—one complete "wobble" in about 26,000 years.

Variations in Gravity

YOU DON'T WEIGH THE SAME everywhere on the earth's surface, and the reason is that the effect of gravity varies from place to place. You would weigh most at the poles where the effect is greatest and least at the equator where it is weakest. Not that the differences would be a matter of any consequence to the weight conscious, they are so slight. The range of variation amounts to only about five parts in 1,000. Weighing machines that depend on balanced levers would not reveal the difference; you would have to use the kind of instrument that measures weight as the amount of stretch or compression of a spring.

And yet, unimpressive as these differences might seem to us at first glance, for the mapmaker, the geologist, the geophysicist, the oil prospector and even the athlete, they hold special significance, as we shall see later.

An astronaut on the moon "weighs" only one-sixth of what he does on earth. This is astronaut James B. Irwin saluting the flag during the exploration of Apollo 15 in 1971.



How Gravity Varies in the Solar System

Planet	Gravity
Mercury	0.37
Venus	0.89
Earth	1.00
Mars	0.38
Jupiter	2.65
Saturn	1.14
Uranus	0.96
Neptune	1.53
Pluto	Unknown

A man who can pole-vault twelve feet high on earth could vault—

- Seventy-two feet high on the moon;
- Thirty-two feet high on Mars;
- But only five feet high on Jupiter.

Reason: Gravity's strength depends in part on the mass of an object. The larger the planet, the greater its pull of gravity.

On the Moon's Surface

- The mass of the moon is a little less than one-eightieth that of the earth.
- The gravitational acceleration of the lunar surface is only about one-sixth that on earth.
- A man who "weighs" 150 pounds on earth "weighs" only twenty-five pounds on the moon.
- Since every movement is exaggerated, astronauts moving about on the lunar surface must operate with measured care.

7. BALLOONING INTO THE SKY

Man has tried many methods to overcome the force of gravity. The one shown here is successful but risky. Balloons filled with helium can indeed carry a man aloft, but control is limited.

What makes gravity vary according to geographic position? Partly, the earth's irregular shape—the bulging middle and a flat top. The result of this fat-flat form, technically an *oblate spheroid,* is that the distance from the center of the earth to the equator is thirteen miles greater than to the poles. Considering that the earth's average radius is 4,000 miles, this difference is actually quite small—about one-third of one per cent. However, Newton's Inverse Square Law still applies: the pull of gravity will be greater at the poles since they lie closer to the point within the earth that behaves as if it contained the whole of the earth's mass.

Other more localized variations which are hard to measure are caused by the nearby presence of massive mountains and by differences in the *density* of the earth's surface and buried rocks in different places; beneath

Interior of the Cathedral at Pisa. According to legend, it was through watching the swing of the sanctuary lamp that Galileo came to realize that the period of swing does not change as the amplitude becomes less and less.

A sky diver goes into an attitude that will use air resistance to make his acceleration toward the ground very much less than 983 cm/sec^2! When his parachute opens, acceleration will vanish altogether.

the earth's thin skin, or crust, matter of wide-ranging densities lies buried and it, in turn, exerts various gravitational tugs on surface objects.

But by far the greatest cause of surface variation is the centrifugal force produced by the earth's spin about its polar axis. Since certrifugal force increases the farther one gets from the axis of rotation, its effects are greatest at the equator. The direction of the force is opposed to the pull of gravity, and so reduces the effectiveness of the earth's grip on things on or above its surface near the equator, thus resulting in an apparent reduction in gravitational intensity. At the poles, by contrast, centrifugal force is zero, and the earth's surface gravity is at its maximum.

Science Bulletin

Prepared by SCIENCE SERVICE

LIMIT ON VARIATION OF THE GRAVITATIONAL CONSTANT

The gravitational constant is a number that relates the strength of a gravitational force to the masses of the bodies producing it. Isaac Newton, who introduced it into physics, based his theory of gravitation on the assumption that it is in fact constant.

Among modern theories Newton's view of the constant is represented by Albert Einstein's general relativity theory. However, the rival theory of Carl H. Brans and Robert H. Dicke assumes that the constant varies with time.

An experiment that could show such variations would be a comparison of gravitational time—the orbital period of a planet—against an atomic clock. This has been done by Drs. Irwin I. Shapiro, William B. Smith, Michael B. Ash, Richard P. Ingalls and Gordon H. Pettengill of the Massachusetts Institute of Technology by timing radar determinations of Mercury's position against an atomic clock.

They report that the variation of the constant can be no more than four parts in 10 billion per year. Continuation of the experiment, they say, could bring the limit down to three parts in 100 billion.

GRAVITY WAVES AND SATELLITES

In June, 1969, Dr. Joseph Weber of the University of Maryland reported the discovery of gravitational waves, energy-carrying waves that involve gravitational forces the same way that radio waves involve electric and magnetic forces.

Dr. Weber's signals come in the form of short bursts from somewhere near the center of the galaxy.

Dr. Weber's records are made at a frequency of 1660 hertz. (The hertz is the unit of frequency measuring cycles per second.) If these same bursts contain a low-frequency component, on the order of one cycle per minute (1/60 of a hertz), says Dr. Allen Joel Anderson of the University of Uppsala in Sweden, they should cause a perceptible wobble in the motion of bodies they encounter. If such a body is a space probe that is sending a continuous tracking signal to the earth, the effect of the wobble should show in the tracking signal.

Dr. Anderson studied the flight of Mariner 6 on 15 March, 1969. There were records covering the times of four gravity-wave events reported by Dr. Weber. In connection with one of these, at 3:41 Greenwich Mean Time on 15 March, 1969, "clearly something unusual happened" to the spacecraft's motion, Dr. Anderson says.

He is continuing his experiment to see if he can find more instances that look like gravity-wave wobble. The determinations are difficult because the waves change the spacecraft velocity by less than 3 millimeters per second, resulting in a displacement of about 10 centimeters. The spacecraft was about 10 million kilometers from earth.

EVIDENCE FOR A CORE IN MARS

One hundred years of earth-observations of the planet Mars had revealed it to be similar to the earth in many respects, but vastly different in others. Man got his first close-up look in 1965 when Mariner 4 flew within 6,118 miles of the planet. As a result of data analysis

from Mariners 6 and 7 (which flew within 2,000 nautical miles of Mars in 1969) it now appears that Mars may be more earthlike than originally thought.

The new data reveal that Mars has a core and that it is probably at least partly molten, says Dr. Don L. Anderson of the California Institute of Technology. Before the occultation experiments performed with the Mariner craft, the precise diameter of the planet, its density and the presence of a core were uncertain. Dr. Anderson measured the precise diameter as 4,208 miles and determined the gravitational pull of the planet on the spacecraft and Mars' two small moons. These coupled with the measurement of Mars' moment of inertia—how its mass is arranged around its axis, including the flattening at the poles—indicate that it is a differentiated body like the earth and has a mantle and core and possibly a crust.

"The core of Mars is much less dense than the earth's but its mantle is denser," says Dr. Anderson. "Indications are that all the core of Mars hasn't yet separated from its mantle . . . which implies that Mars hasn't gotten hot enough to melt all the iron, sulfur and nickel, which are the core-forming materials."

A BLACK HOLE IN THE GALAXY

According to theorists of gravitation a black hole is a star or similar object that has been so condensed by its own gravity that its gravitational field is too strong for any matter or even light to escape from it. It is thus totally cut off from the rest of the universe.

Dr. A. G. W. Cameron of Yeshiva University in New York City believes there is such a black hole or collapsar, as he calls it, in our own galaxy. He says it is the dark companion of the star Epsilon Aurigae.

Epsilon Aurigae is what is called an eclipsing binary. Two stars, one bright and one dark, are bound together by gravity and revolve around each other so that part

of the bright star's light is periodically cut off by the dark one. Dr. Cameron says that Epsilon Aurigae differs from other eclipsing binaries in that its eclipses are caused, not by a single solid disk, but by a swarm of small dark particles. "You can see the difference in the light curve (the graph of brightness over time)," he says.

He suggests that the swarm of particles is bound to and orbiting around a central unseen object, the black hole. There is no way to prove this positively. All that astrophysicists can do, a kind of negative proof, is to rule out all other possible explanations, until the black hole is the only one left.

OLD FAITHFUL STRAIN GAUGE

Old Faithful geyser isn't entirely faithful; the interval between its eruptions varies slightly, and this variation, according to John S. Rinehart of the National Oceanic and Atmospheric Administration, reflects variations in tectonic stress in the earth around the geyser's underground plumbing.

The NOAA physicist has found a correlation between earthquake activity and the eruption patterns for three well-known geysers—Old Faithful and Riverside in Yellowstone National Park and Old Faithful of California at Calistoga, California. Rinehart found that two to four years before every major earthquake within sixty miles of Old Faithful at Yellowstone the interval between eruptions began to decrease, reaching a minimum near the time of the quake and rising again afterward.

In 1956, for example, the geyser's period began decreasing rapidly until August, 1959, the time of the 7.1-magnitude Hebgan Lake earthquake centered twenty-eight miles away.

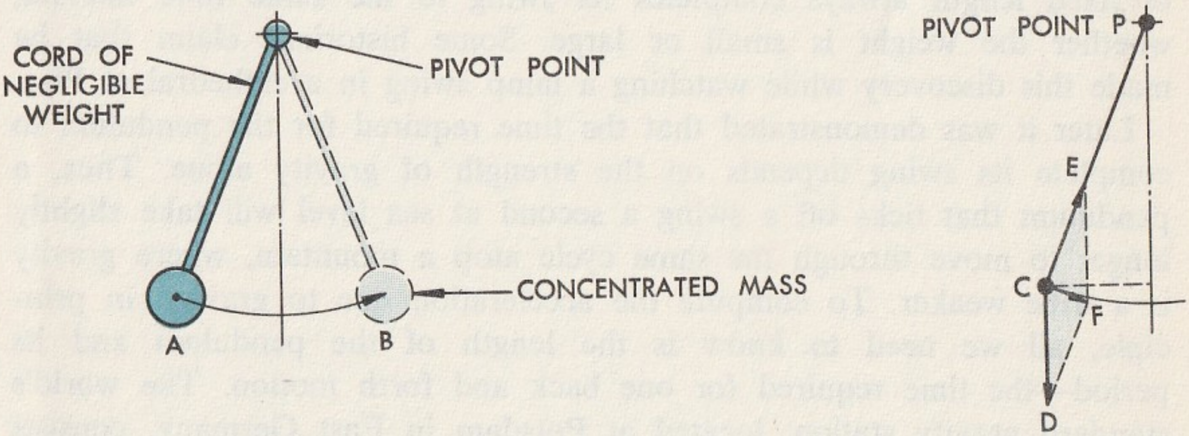
What the "Gal" Means

SCIENTISTS USUALLY EXPRESS the pull of gravity in terms of the acceleration of free-falling bodies. The unit used to specify this acceleration has been called the *gal,* named in tribute to Galileo.

The unit equals one centimeter per second per second, commonly written 1 cm/sec^2. Over the earth's surface the pull of gravity ranges from 978 gals (at the equator) to 983 gals (at the poles). If, for example, you dropped a ball from an airplane above the North Pole, it would fall faster and faster, gaining speed at the rate of 983 centimeters (about thirty-two feet) every second. At the end of two seconds, the ball would be moving at the rate of 1,966 centimeters (just over sixty-four feet) per second. And after each succeeding second the speed will continue to increase by 983 centimeters per second. At the equator, the rate of an object's fall would be appropriately slower, increasing by only 978 centimeters per second, as second followed second.

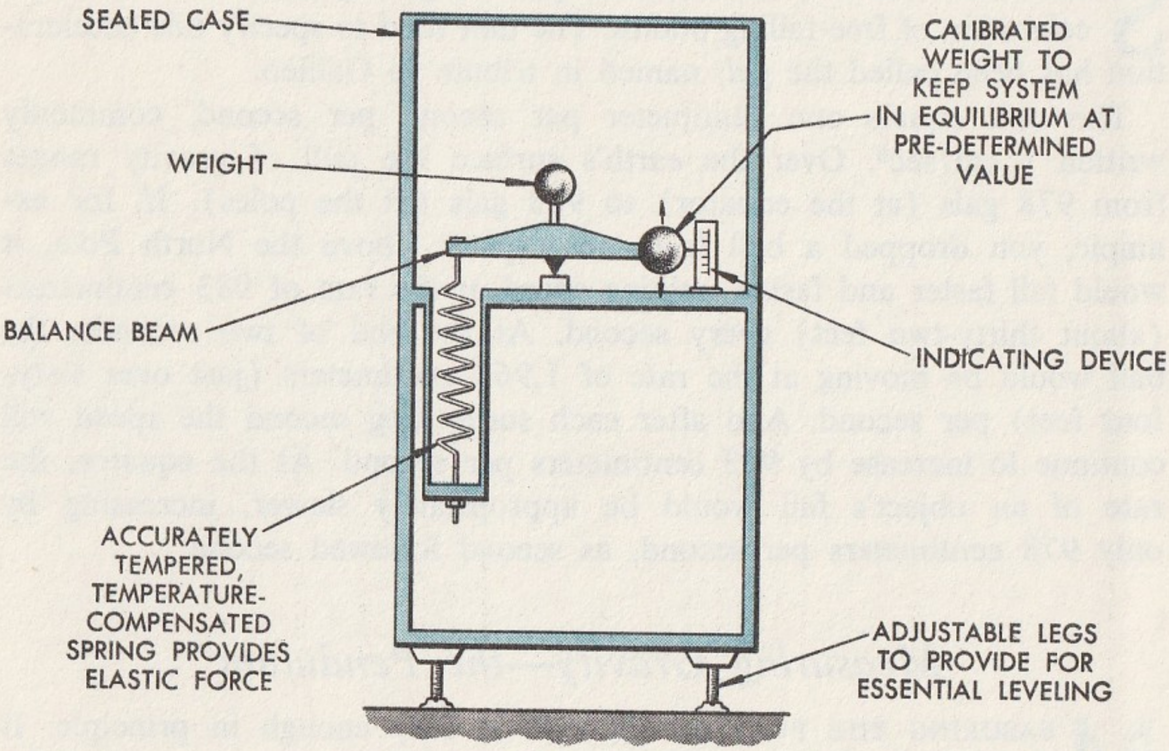
Measuring Gravity—the Pendulum

MEASURING THE PULL OF GRAVITY is easy enough in principle. It could be done very readily with a simple pendulum consisting of a small weight suspended from a nonstretchable and virtually weightless



Two forces act upon the mass at C: CD is the force vector due to gravity. CE is the force vector due to the pull in the cord toward pivot P. The resultant force due to imbalance is shown by vector CF. The mass then accelerates in that direction until it reaches the point vertically beneath the pivot, beyond which gravity decelerates it until it stops; the process is then reversed.

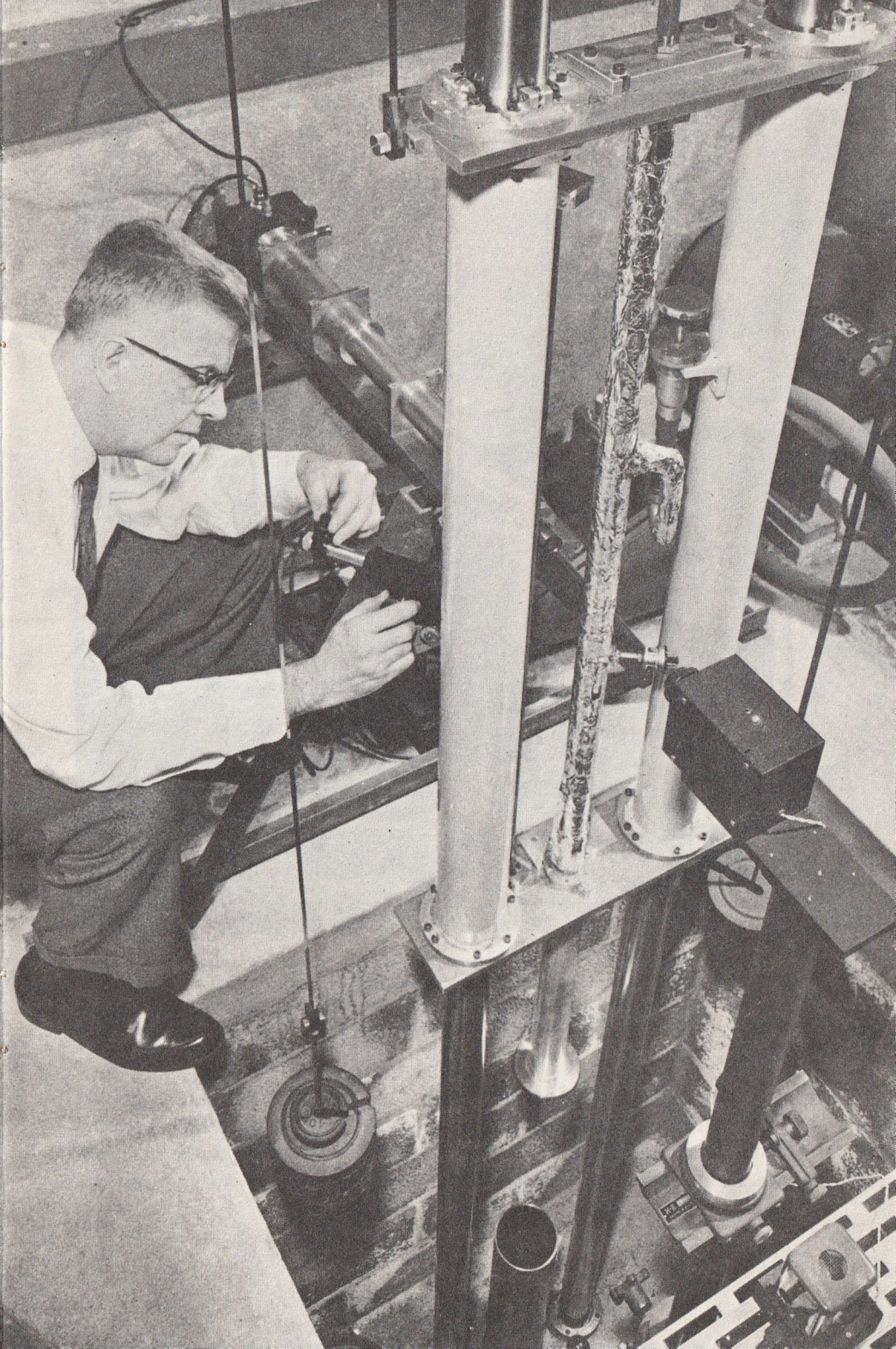
SIMPLIFIED GRAVITY METER



string! When Galileo was a young man, he discovered that a pendulum of fixed length always completes its swing in the same time interval, whether the weight is small or large. Some historians claim that he made this discovery while watching a lamp swing in a cathedral at Pisa.

Later it was demonstrated that the time required for the pendulum to complete its swing depends on the strength of gravity alone. Thus, a pendulum that ticks off a swing a second at sea level will take slightly longer to move through the same cycle atop a mountain, where gravity is a trifle weaker. To compute the acceleration due to gravity, in principle, all we need to know is the length of the pendulum and its period—the time required for one back and forth motion. The world's standard gravity station, located at Potsdam in East Germany, consists

(*Right*) The National Bureau of Standards uses this equipment to redetermine a physical *constant*—the acceleration of gravity. As an object drops through the evacuated foil-covered tube, its motion is timed with extreme precision.



A University of Wisconsin geophysicist takes a gravity reading, one of more than half a million taken around the world in a ten-year period to learn the exact size and shape of the earth and the nature of its interior.

of a gravity pendulum so accurate that it can measure the earth's gravity to one part in ten million. There, measurements have established the value of gravitational acceleration as 981.274 cm/sec^2. Such precision comes from timing of thousands and even millions of swings and ascertaining their average.

The Gravimeter

THE MOST COMMONLY USED INSTRUMENT for making gravity measurements is the *gravimeter*—a highly sensitive version of an ordinary spring scale. The earth's gravitational pull is determined by measuring the amount of stretch of a thin wire, made of an alloy of nickel and steel, called *invar,* from which a small weight is suspended. The greater the gravitational intensity, the more an object will "weigh" and the farther it will stretch the wire. The gravimeter is compact and portable and may be carried anywhere, since it weighs only a few pounds. Readings can be made in three to five minutes.

There is one drawback, however—where the pendulum gives absolute values of gravity the gravimeter provides only comparative readings between one point and another. To get an absolute reading with the gravimeter it is necessary to refer the gravimetric finding to a base station where the absolute value has already been obtained, such as the one at Potsdam.

Measuring Free Fall

THE MOST DIRECT WAY to measure gravity on land is to gauge the acceleration of a freely falling body in true Galilean tradition. But, until recently, it was not possible to do so precisely. The event happened too quickly.

Now, however, it has become possible to measure free fall with high precision. It is done by dropping a slotted quartz bar and measuring the speed with which the bar falls. The timing mechanism consists of light beams and photoelectric cells, or electric eyes. As the bar drops, the light beams pass through the slots in the bar and trigger the photoelectric cells so that they conduct electricity. These triggering actions are timed exactly, and thus the rate of fall from triggering station to triggering station can readily be calculated, and from it, acceleration.

By this time you have probably guessed some of the reasons specialists in many fields find it necessary to know the point by point variations in the force of gravity over the earth's surface.

Since geologists cannot make trips to the earth's interior, they must rely upon analysis of gravity variations as one of the most important tools for helping them to understand the composition of matter buried beneath their feet. In much the same way, the oil prospector, one who is expert enough to recognize specific changes in densities in the earth's crust from a study of gravitational variations, might uncover a real gusher and turn this knowledge into huge profits.

Even athlètes have become intensely interested in the geographical variations in gravity. It's more than scientific curiosity. World-wide mapping of gravity's ups and downs affects track and field records. Pole vaulters, javelin throwers and high jumpers all battle gravity. Were an athlete to expend the same effort in different regions of the world, chances are he would make different scores, since the force against which he strains varies from place to place. If all other things were equal, a javelin thrower should hurl his javelin twenty inches farther in Mexico City, for example, than in Tokyo, Japan, because Mexico City is closer to the equator. Someday officials may take gravitational corrections into account when they compute world records.

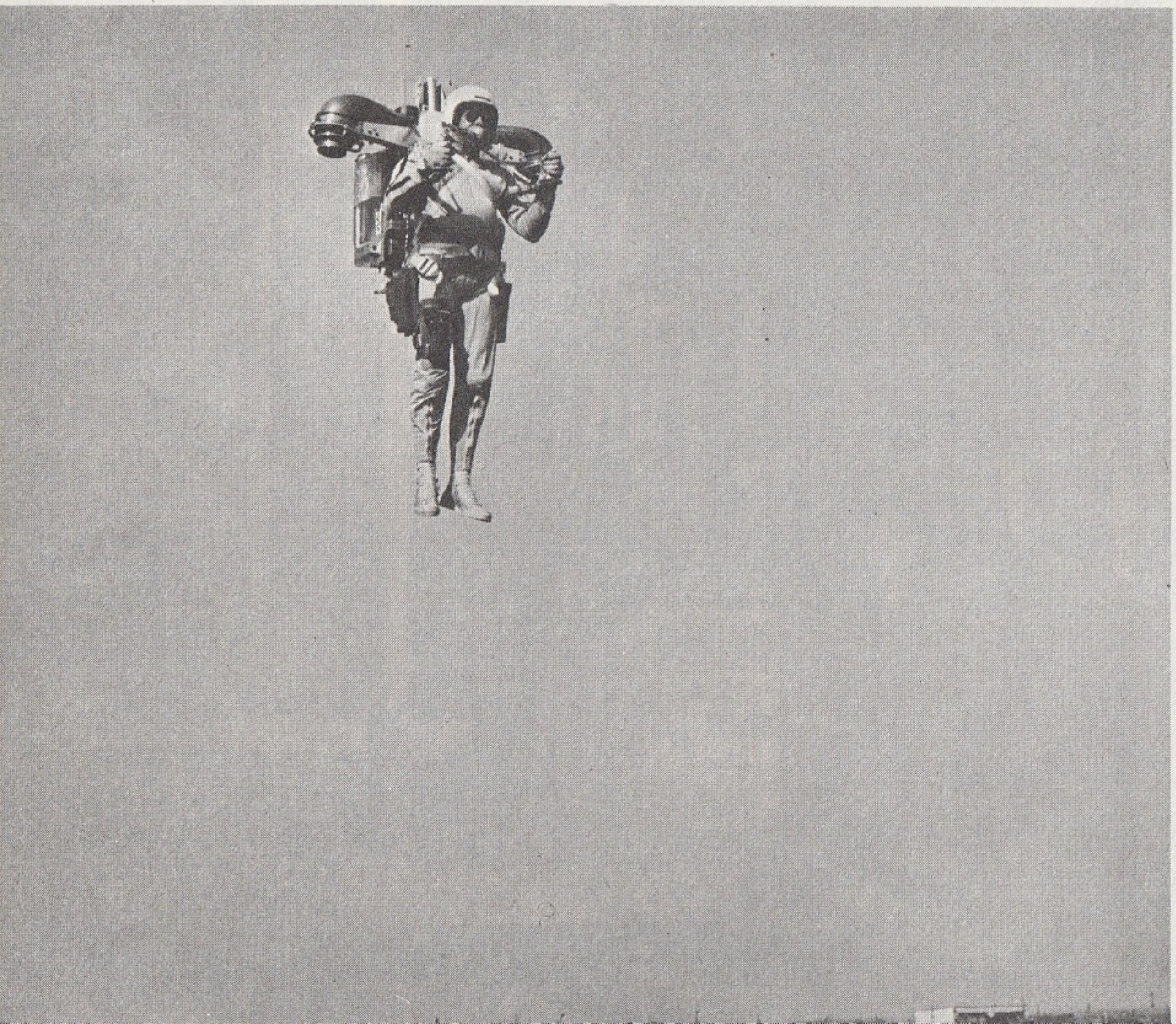
(*Right*) A pole vaulter strains every muscle to force his body in a direction opposite to the pull of gravity. Even for an expert, sixteen feet is no easy jump.


MILLROSE
A.A.
INVITATION
POLE
VAULT
107

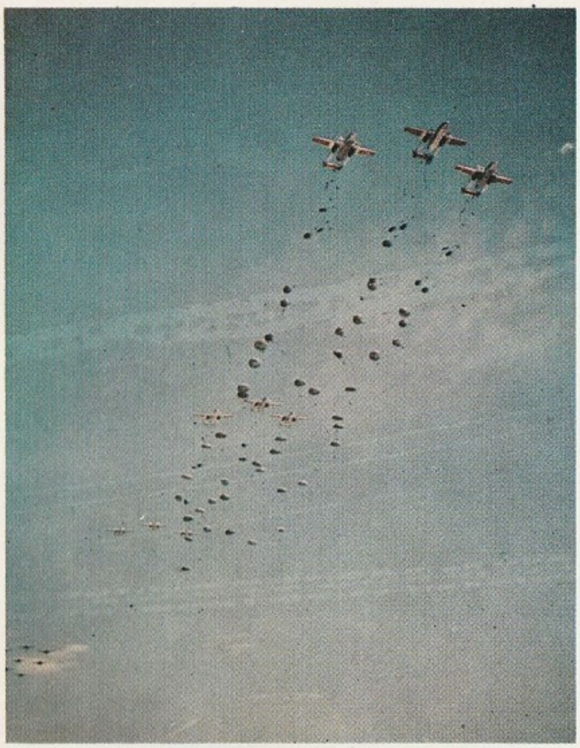
Mapping the Geoid

IT IS PERHAPS THE SCIENCE OF *geodesy*—the measurement and mapping of the globe—which derives most benefit from the study of gravity differences. Geodesists today are busily at work trying to determine the true shape of the earth. What they are anxious to do is map the *geoid*—the sea-level shape of the globe. By collecting global gravitational measurements, and correcting all their findings to a sea-level reading, they hope to be able to ascertain exactly the earth's departure from true sphericity. Mapmakers will immediately put this information to important use. For even in this age of very accurate navigation, there is still a surprisingly large uncertainty in distances from continent to continent. For example, the relative nearness of North America to Europe is known only to within about 400 feet; and that of North America to Asia is known

One way to defy gravity: a jet-powered back-pack to lift and carry you along a 300-foot journey.



Gravity can work for you as well as against you. Here, it assists the parachutists as they head earthward and toward the target area. But the aircraft must constantly counteract the force of gravity to maintain altitude.



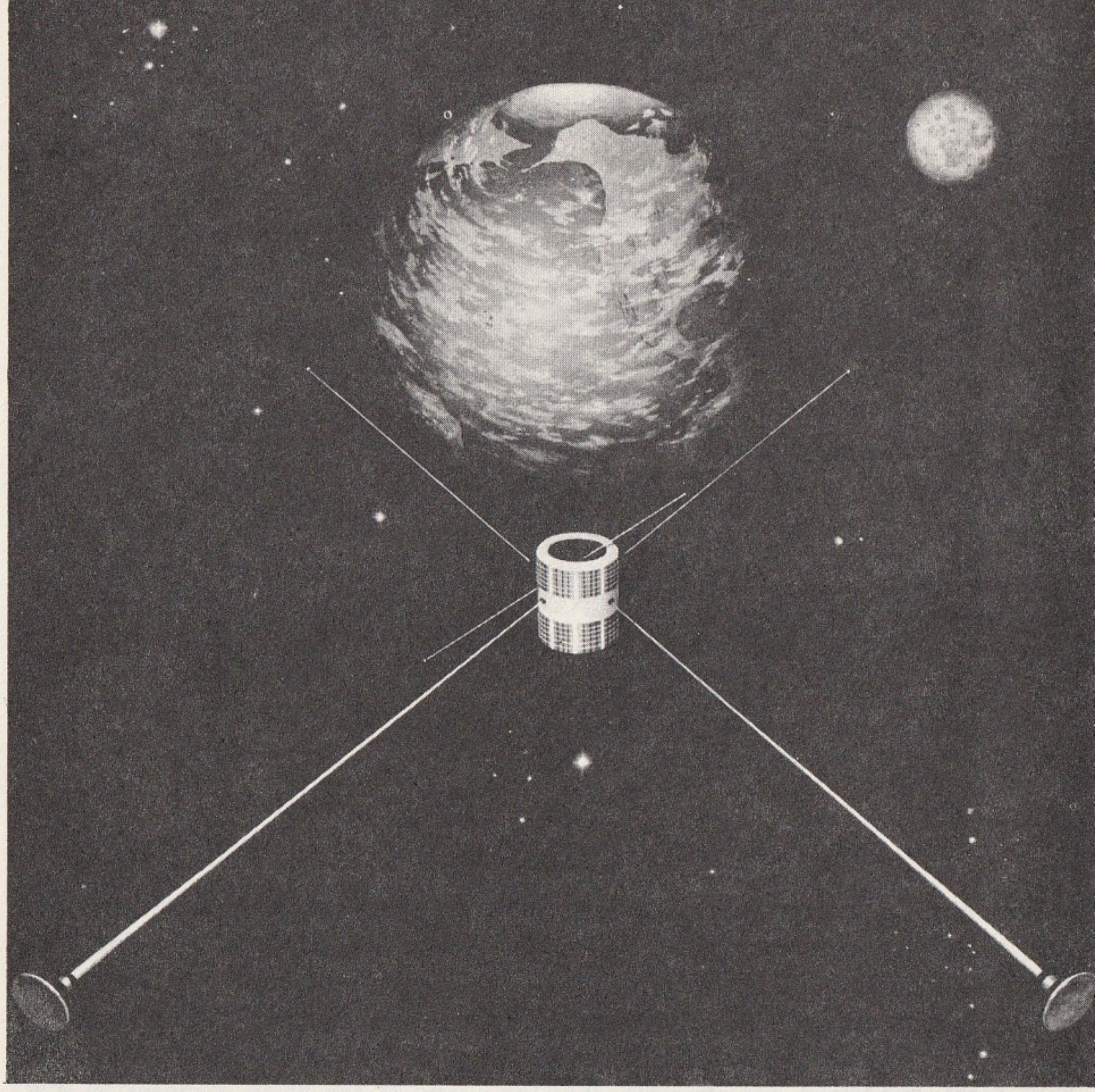
8. MASS PARACHUTE DROP

only to approximately 1,200 feet. With new data mapmakers will be able to erase these uncertainties from their charts. Specially designed satellites are already helping to supply the maximum geodetic information and eliminate these plaguing ambiguities. (A study of the orbit of Vanguard I, the grapefruit-sized satellite launched early in the United States space program, suggested, for example, that the shape of the earth is closer to that of a pear than that of a tomato.)

Gravity and Space Travel

COULD YOU DATE THE BEGINNING of the Space Age? Would you say, as some do, that it was 4 October, 1957, when Russia amazed the world by launching Sputnik I, the first artificial satellite, into orbit? Or might it have been in 1926 when Robert Hutchings Goddard—called by many "the father of rocketry"—fired the first liquid-propelled rocket some 200 feet high?

More than likely, there would be no disputing the year 1687—the year Sir Isaac Newton published his *Principia*—as the jumping-off point. If we compared space travel to some cosmic chess game, we might say that



Artist's concept of the "gravity gradient" system used by the Application Technology Satellite (ATS-E). Four 123-foot-long booms are deployed after the satellite is placed in a stationary orbit 23,000 miles above the earth. The forces of gravity, which cause the moon continually to expose only one side to the earth, exert a similar influence on ATS-E, "capturing" the booms and stabilizing the spacecraft.

Sir Isaac set down in this great document the rules by which the game was to be played. His "instructions" were rather explicit, even going so far as to predict and explain artificial satellites. But, alas, he couldn't play the game except in his own imagination. To play the game required some very complicated pieces. And these pieces only came later with the birth

of the engineers, the physicists, the rocket propulsion men who build the powerful rockets which boost the vehicles into space.

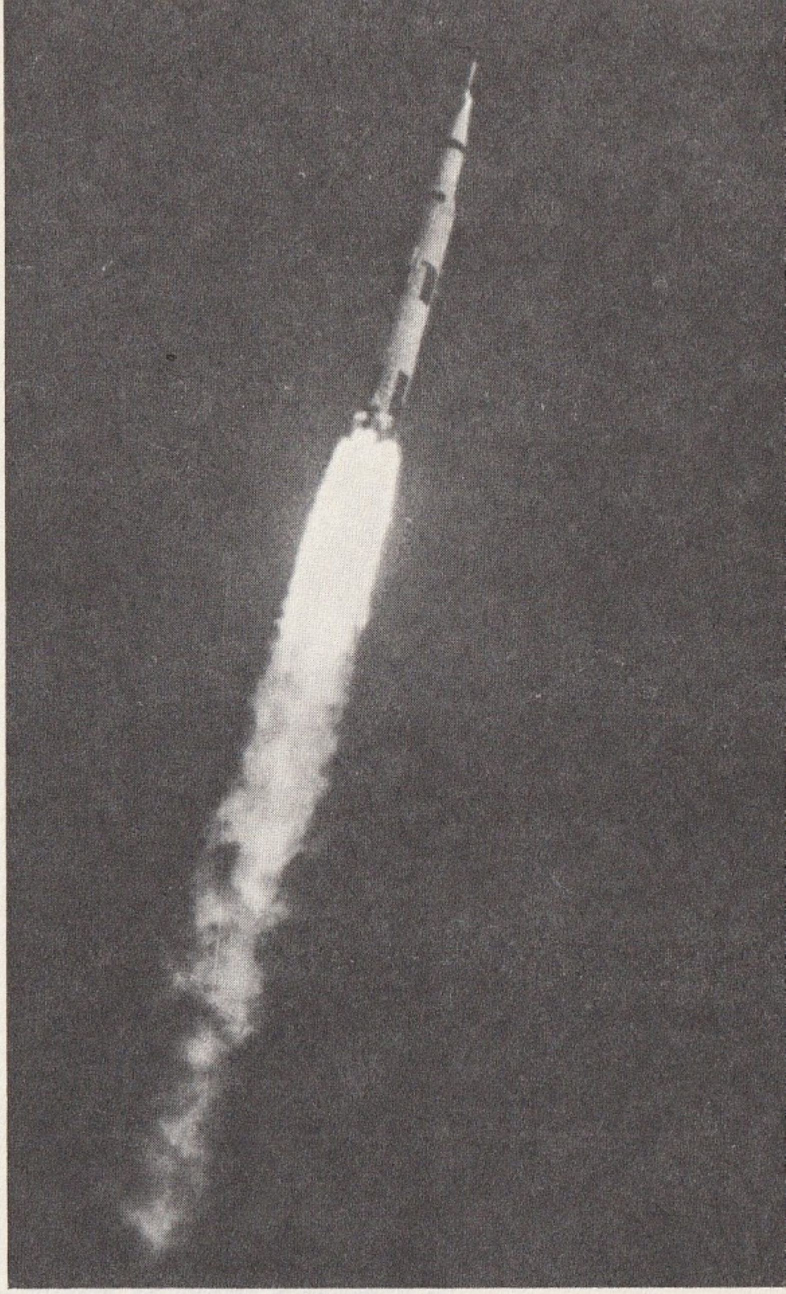
In addition to the Law of Universal Gravitation, the *Principia* contained Newton's Three Laws of Motion, which govern all aspects of space flight. The Third Law explains the action of rockets that makes it possible for space vehicles to leap free of the earth's gravity. It says that to every action there is an equal and opposite reaction. If you press on a wall (action), the wall presses back on you (reaction). When a child releases an inflated balloon with the rubber removed from its neck, the air rushes out (action) and the balloon whooshes forward (reaction). As a rocket

9. ACROBATICS WITH A TRAMPOLINE

Most children have been scolded for bouncing on their beds—early attempts to overcome gravity. This man is doing it the proper way and with great skill.

kicks out high-speed exhaust from its rear (action), the rocket is shoved in the opposite direction (reaction).

Of course, in order to lift off from its launching pad, a rocket must have an acceleration greater than the acceleration downward due to the earth's gravity (thirty-two feet per second per second at sea level). It is Newton's Second Law which tells scientists how much fuel will be required to obtain successful lift-off. According to the Second Law, when a force (in this case the thrust of the rocket) acts upon a mass (the rocket body), an acceleration will be produced in the direction along which the force acts. Some rockets are launched with forces of nine g's (nine times the force of the earth's gravity) or more. Fortunately, such force does not need to be applied for very long. But while it lasts, the "human payload" cannot expect to be comfortable, even in his specially contoured seat! He weighs nine times as much as normal. America's first astronaut, Alan B. Shepard, experienced about eight g's at lift-off. For a few seconds the American spaceman was pressed into his seat with a force of hundreds of pounds. His chest sagged as if a heavy slab of



Action and reaction: as expanding gases gush downward out of the Saturn V rocket's exhaust with a powerful thrust, an equal force in the opposite direction causes the rocket and its payload to rise against gravity. This is Apollo 8, the first manned spaceship ever to escape earth's gravitational influence and fly to the vicinity of the moon.

concrete were jammed against it, and each leg felt as if it weighed several hundred pounds.

Once the rockets have burned out, and a space vehicle intended to orbit the earth has been powered, Newton's First Law takes over, namely: any body in motion will continue to move in a straight line at a constant speed unless some other force acts upon it. Thus, were it not for the force of gravity the capsule would move farther and farther away from the earth in a never-ending arrow-straight course. But as the capsule tries to pursue an undeviating route, the earth's gravity makes it depart from its straight-line course, bending it back toward the earth, so that it completes its orbital loop.

10. ASTRONAUTS: ANTI-GRAVITY EXPERTS

America's pioneering Mercury astronauts were the first to experience effects of greatly increased gravity during blast-off and—when in orbit—no gravity at all.

What Is Orbital Velocity?

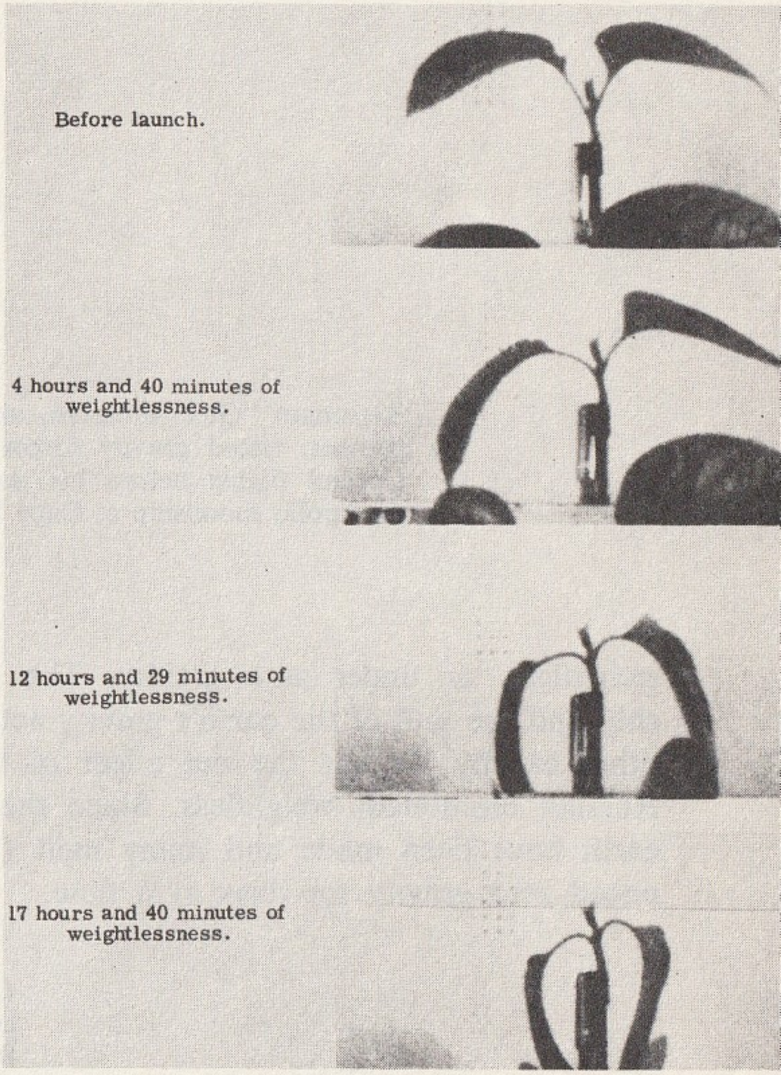
THE MINIMUM ALTITUDE for orbiting an artificial satellite is about eighty to 100 miles. Below this altitude the earth's atmosphere is too dense; the satellite would burn up with the heat of friction with the air. To achieve this air-skimming orbit so close to earth, the vehicle requires a speed of about 18,000 miles per hour.

Orbiting speed diminishes, however, as altitude increases—since the force of gravity decreases with distance. To make this clear we might

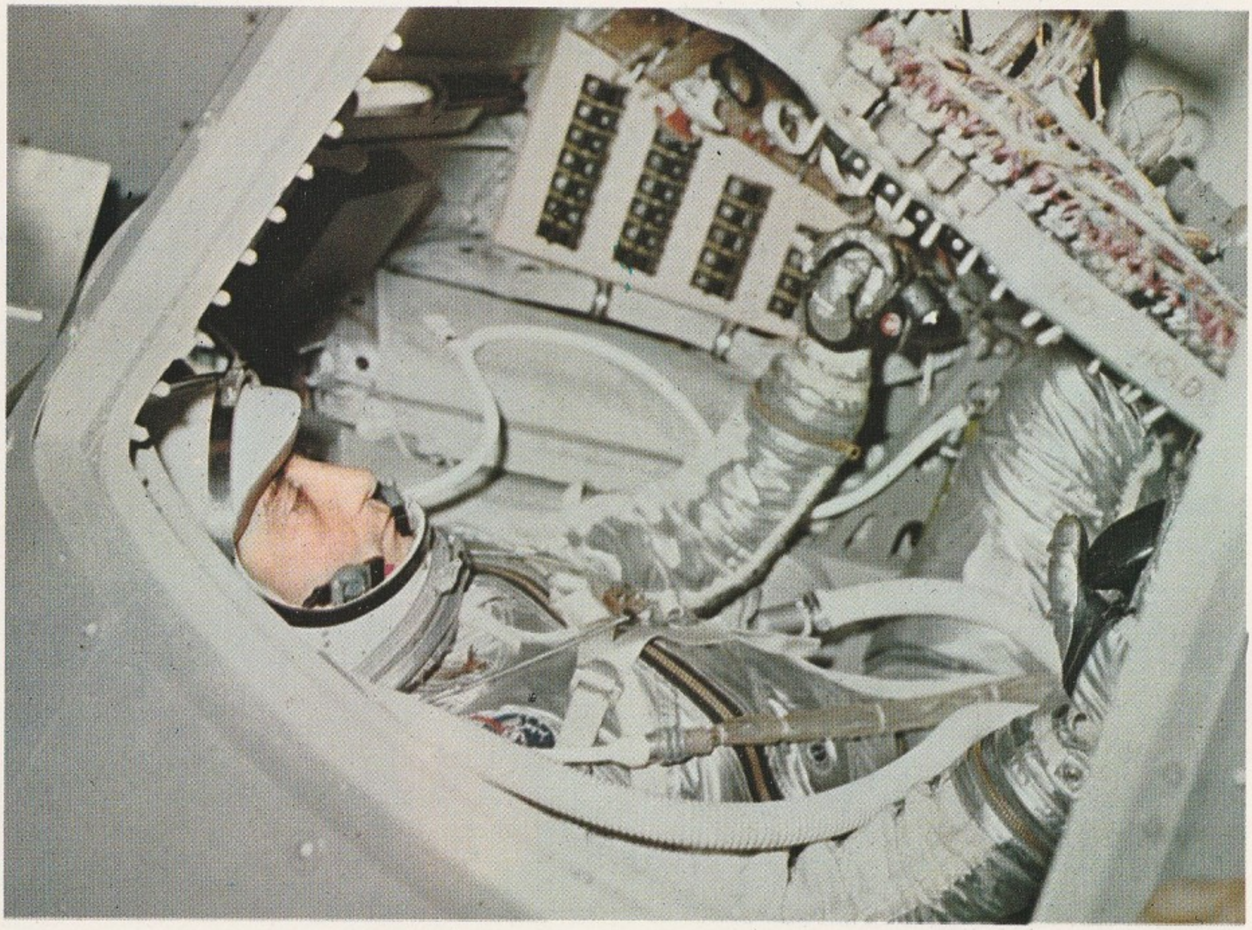
return to our illustration of the weight whirled at the end of a string. The shorter the string length the faster you have to twirl to keep the string taut. But as you increase the length of string, orbiting speed is reduced.

Thus, at an altitude of 300 miles a satellite would require a speed of about 17,000 miles per hour to go into orbit. And when we hurl an artificial satellite into the same orbit as the moon, it has the same cruising speed as the earth's natural satellite—2,000 mph.

On 12 April, 1961, a young Russian air force pilot, Major Yuri Gagarin, became the first man to orbit the earth. He made his extraglobal circuit in 89.1 minutes. For a large part of the time the Russian was



This is what happens when a pepper plant is removed from earth's gravitational pull and placed in orbit, where it is weightless—in a state of zero gravity. The photos were taken in flight by a specially built 16mm camera. The plants grew in darkness, except for photo flashes every ten minutes. Plant roots were sealed into plastic containers filled with a spongelike material to provide water during the flight.

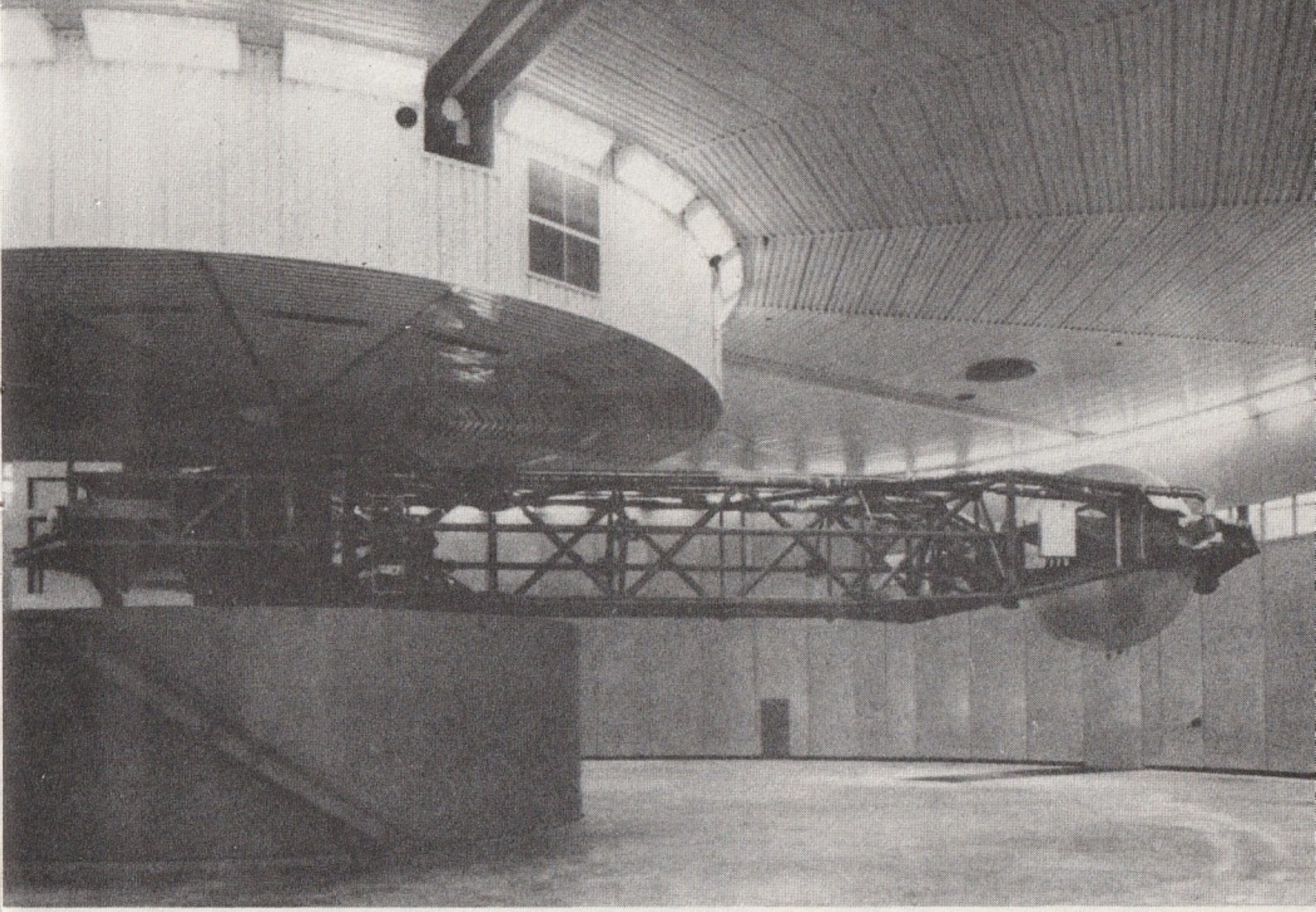


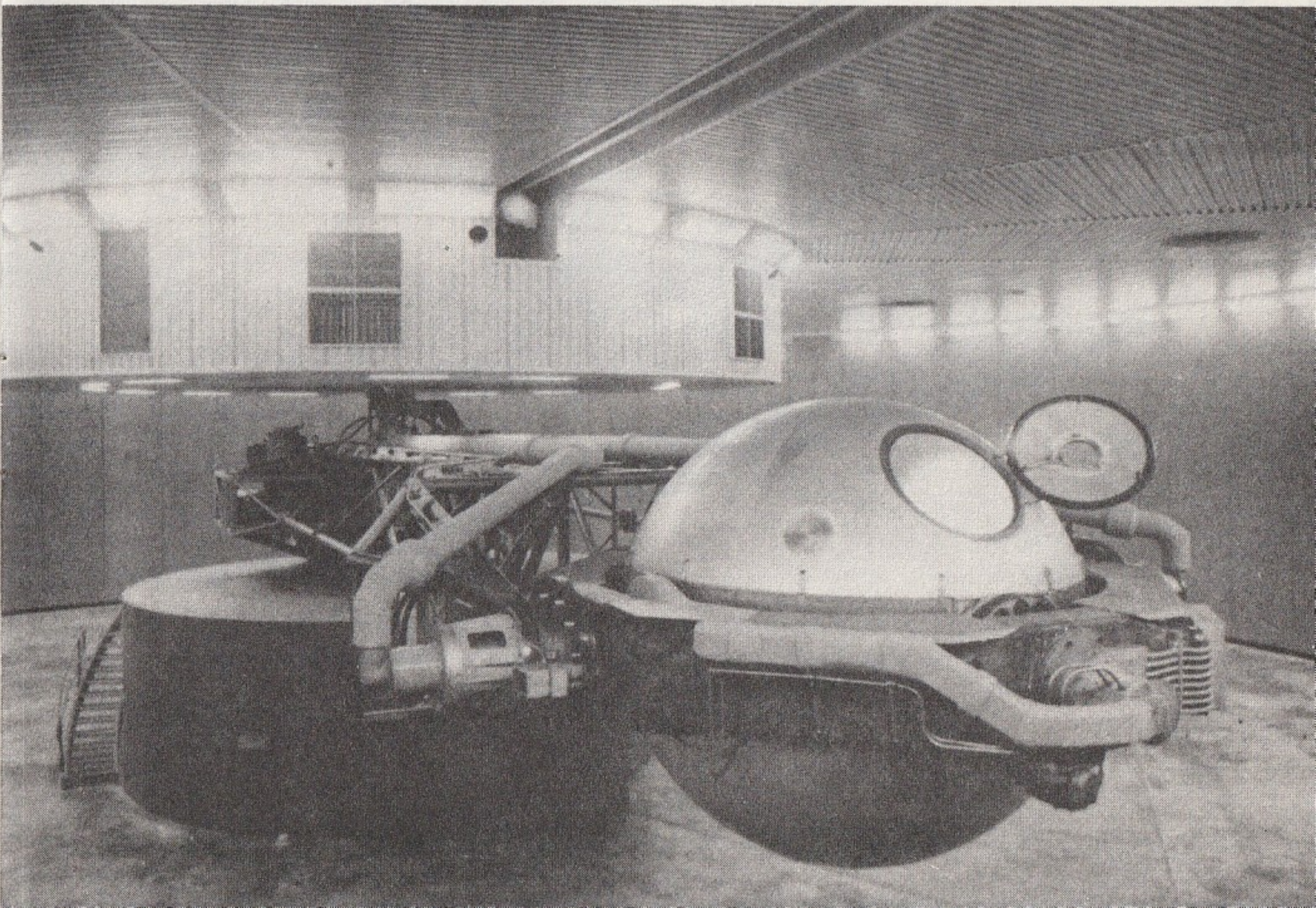
11. ASTRONAUT VIRGIL I. GRISSOM

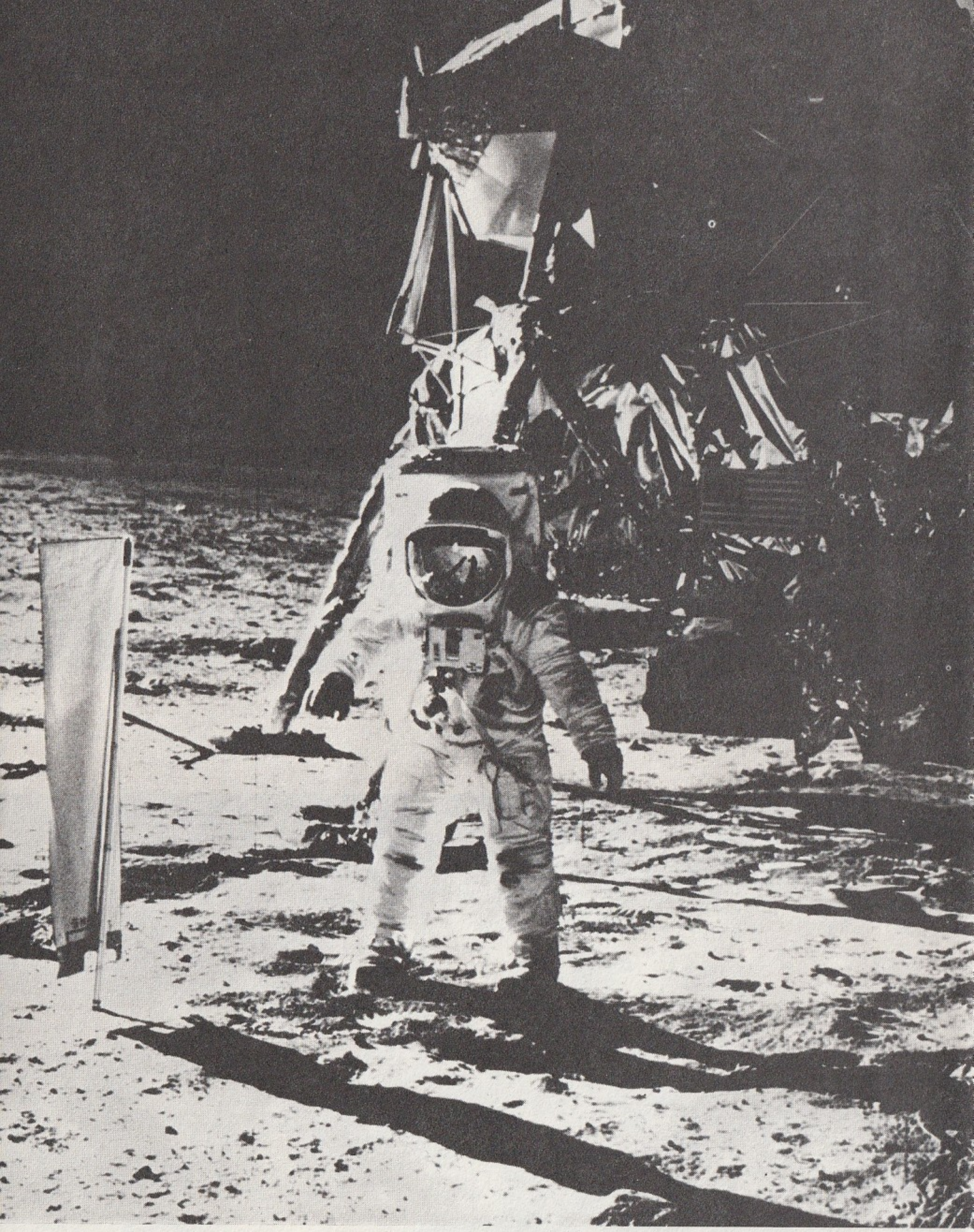
Astronaut "Gus" Grissom, an American space pioneer, tested gravity forces in Mercury and Gemini flights before his accidental death in an Apollo moonship at Cape Kennedy in 1967.

weightless, or under zero gravity. The centrifugal force of his spaceship and the pull of the earth's gravity acted so as to counterbalance each other exactly. It was the net effect of this tug of war that made the Russian cosmonaut weightless. Since then many hundred orbits of the earth have been made and many men (and one woman) have experienced zero gravity for days at a time.

(*Right*) Centrifuge at U.S. space center in Houston, Texas, is used to train astronauts. It has a fifty-foot arm which can swing a three-man gondola to create g-forces men experience during blast-off and re-entry.







Astronaut Neil A. Armstrong of Apollo 11, the first man to walk on the moon. Because the moon's gravitational pull is only one-sixth that of earth, his 120-pound backpack "weighed" only twenty pounds!

You have experienced weightlessness briefly if you have ever been in a state of free fall as, for example, when you jumped off a diving board. Aside from the slight air resistance, you felt weightless during your entire arc before striking the water.

Artificial Gravity

SOME SPACE MEDICINE EXPERTS are worried that prolonged exposure to weightlessness might prove physically and psychologically harmful to a spaceman. They point out that the human organism develops entirely in a one g environment. Abruptly, the spaceman is transported to a state where he has no weight. We now have ample evidence that astronauts can tolerate zero g for a few hours or even days or weeks without deleterious effects. But what will happen to the spaceman whose trip lasts several months? As yet there is no answer to this question. Weightlessness for this duration cannot be reproduced on earth.

Even if the dangers of prolonged weightlessness should prove minimal, scientists believe that the space crew will feel more at home if a sense of gravity is introduced into the spaceship.

"Artificial gravity" can be provided by centrifugal force if a space vehicle is made to rotate at a suitable speed. While centrifugal force is not exactly the same as gravitation, human beings in orbit could not tell this pseudo-gravity from the real thing. As soon as the vehicle started to rotate, the crew would have weight again. They would tend to move toward the outermost walls of the ship just as earth objects tend to move toward the middle of the earth. When a spaceman exclaims that he is "falling down", he will actually be moving toward the walls of the spinning ship. With synthetic gravity, the space crew would not feel so much like aliens while they put in their tours of duty in this strange environment.

Escape Velocity—the Moon Route

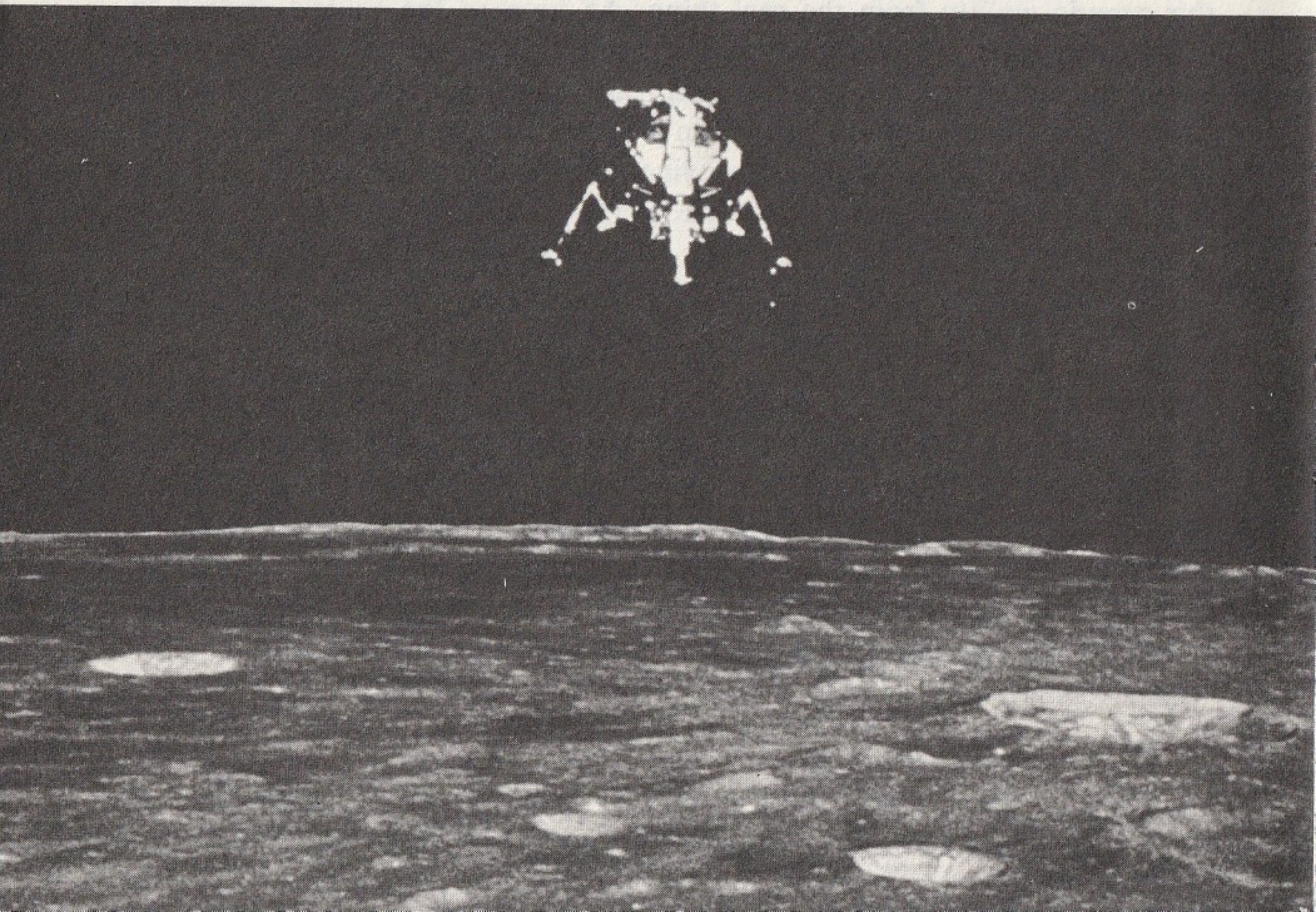
LET US SUPPOSE that we were able to drop an object—say an apple—from the moon to the earth. What would be the apple's speed just before its impact with the earth? The answer is: about seven miles per second, or about 25,000 miles per hour (discounting air resistance). This is an especially significant figure; it is the speed necessary for a vehicle striking out from the earth's surface, on a journey into interplanetary space, to escape the planet's gravitational pull. Scientists call this the *escape velocity*.

For a specific example of the role gravity plays in moon travel, consider the flight of Apollo 8 in 1968—the first time that man rocketed beyond the earth's gravitational grip and flew to the vicinity of the moon. Almost from the beginning of that flight, commanded by astronaut Frank Borman, success depended on mastering the complex forces of gravity.

We know that gravity's pull affects a spaceship in the same way it affects celestial bodies. We know also that if the spaceship travels at a precise speed after launching from Cape Kennedy—17,400 miles an hour in the case of Apollo 8—the effect of earth's gravity will be counterbalanced by the craft's centrifugal force and the ship will go into earth orbit. That is what happened after Apollo 8 was launched—it went not straight for the moon, but into a temporary "parking orbit" around earth.

A new gravitational problem then arose—how to give the Apollo craft enough new rocket power to get it to the moon's vicinity, but not so

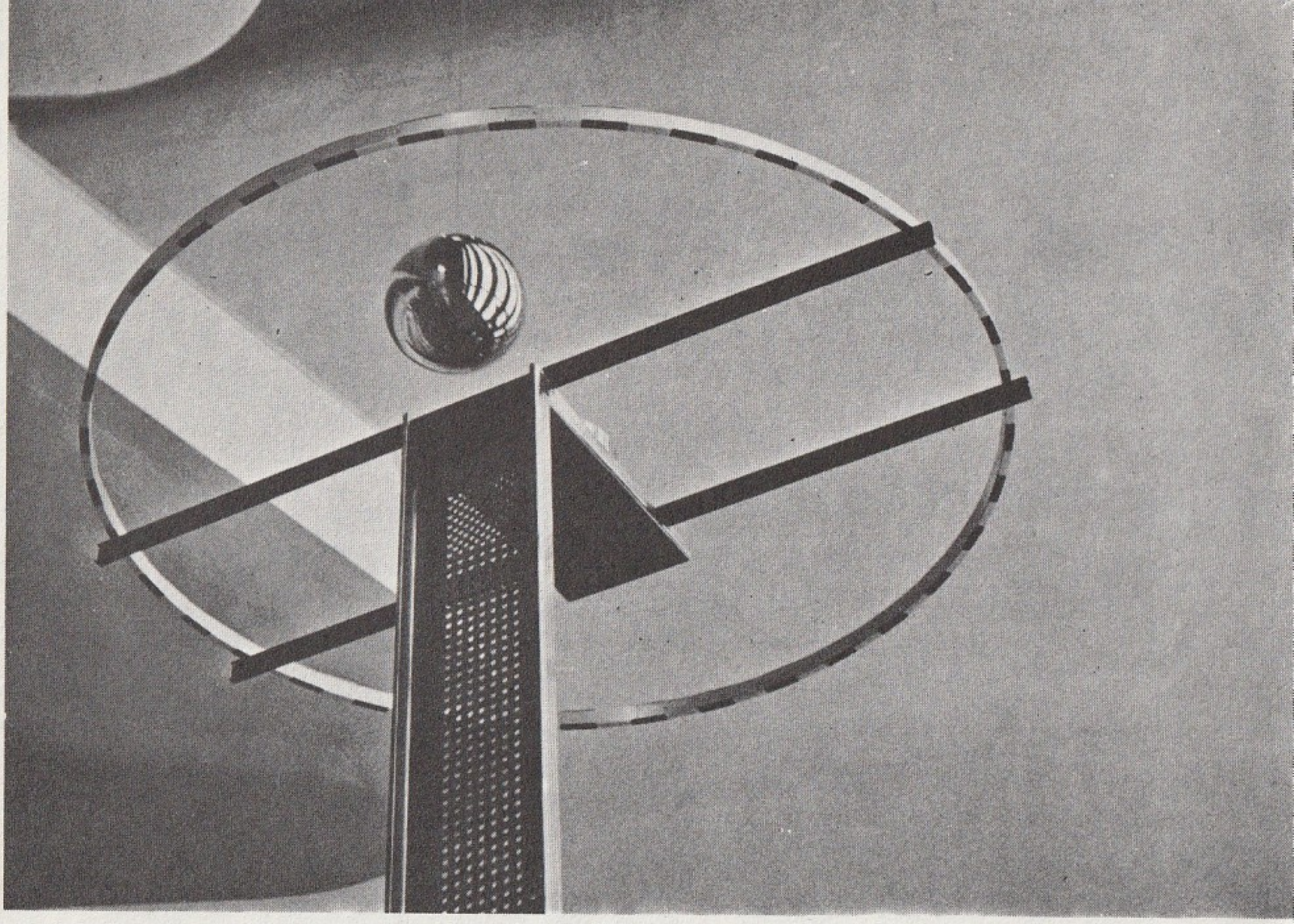
The lunar module "Intrepid" with astronauts Charles Conrad and Alan Bean, heading for the Apollo 12 landing site, Ocean of Storms. It was the second U.S. moon landing. Difference in gravitational pull of moon and earth created new and difficult landing problems for Apollo crewmen.



The unaccustomed effects of zero gravity for an astronaut outside his orbiting capsule make a "space walk" a feat of great difficulty. This is Edwin Aldrin outside Gemini 12 in 1966.

much impetus as to break the bonds of earth's gravity altogether, sending its crew on a tragic course from which they never could return.

To explain: A spacecraft escapes from the earth's gravitational field when it reaches a speed of more than 25,000 miles an hour, as we have noted. If Apollo 8 had reached that speed, and then missed the moon, it would have kept going into deep space until it entered the gravitational field of the sun and became its eternal satellite.



The Foucault Pendulum installed in the main lobby of the General Assembly Building at the United Nations consists of a 200-pound gold-plated sphere suspended on stainless steel wire, seventy-five feet long. The motion of the sphere demonstrates, visually, the rotation of the earth.

When Apollo 8 finally left its "parking orbit" it headed toward the moon at a speed of 24,200 miles an hour—slow enough to keep it within the pull of the earth. This pull gradually slowed the ship to a speed of 2,216 miles as hour when Apollo 8 was within 38,900 miles of the moon. At that point, the moon's gravitational pull on the craft became stronger than the earth's. Apollo 8 had left the earth's sphere of gravitational influence and entered the moon's.

As the moon's pull increased, the coasting Apollo 8 began speeding up and reached a velocity of 5,700 miles an hour just before the crew wanted to go into lunar orbit. It was at that point that Apollo's retro-rocket engine was fired, slowing the craft to 3,720 miles an hour—the speed that exactly counterbalanced the moon's gravity and enabled Apollo 8 to go into lunar orbit. Now Apollo 8 became a satellite of the moon, and both were orbiting the earth in the same general path.

Finally, to escape the grip of the lunar gravity, Apollo 8 again fired its engines to speed up to 5,400 miles an hour. Thus breaking the bonds

of the moon, Apollo 8 headed back home, coming increasingly under the earth's gravitational influence once again. The ship picked up speed gradually, until it hit the earth's atmosphere at almost 25,000 miles an hour.

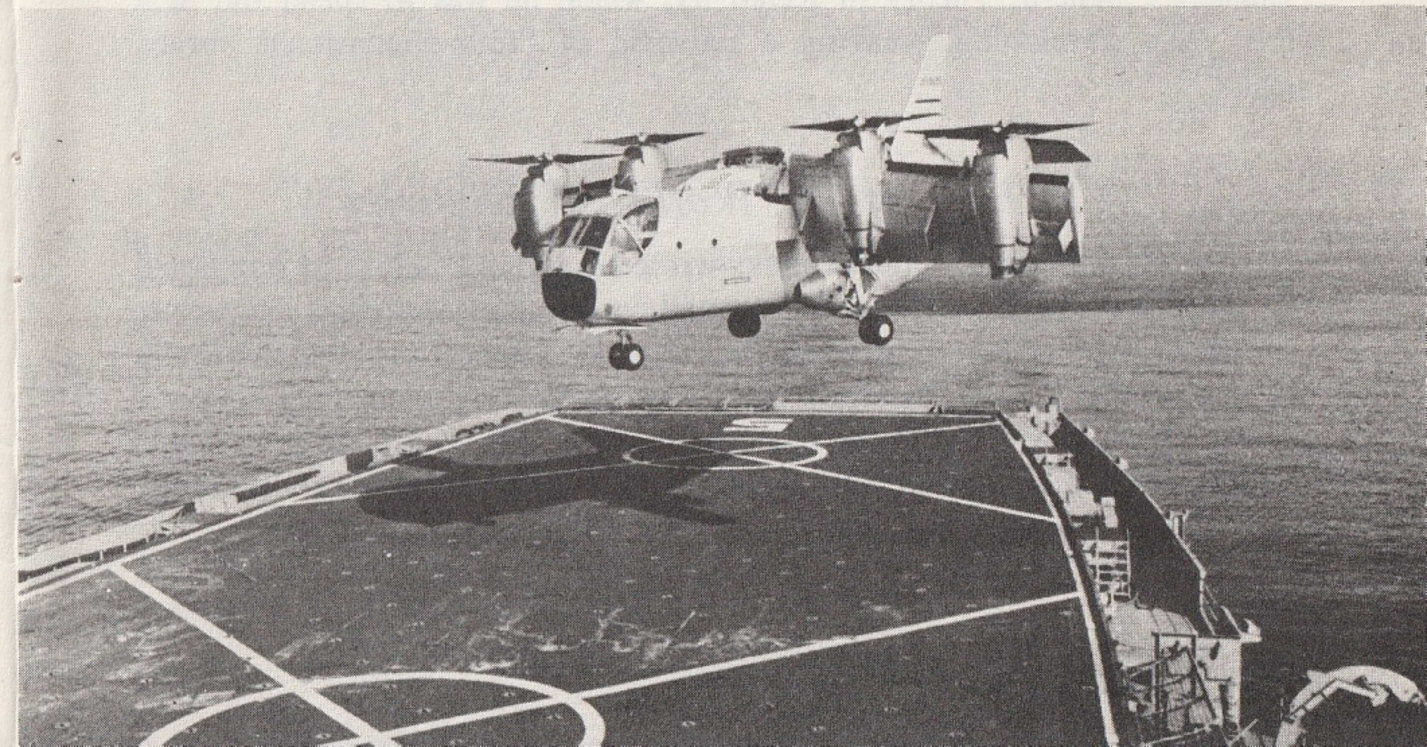
Apollo 8—and its successors in the moon-travel series—proved what theorists on earth had long imagined: gravitation may be mysterious, but the effects of gravity can be "controlled". Thanks to three of the all-time giants of science—Galileo, Newton and Einstein—scientists can describe and predict the way in which gravitation works.

The Genius of Albert Einstein

In the year 1916, Albert Einstein published a treatise called *General Theory of Relativity,* in which he stated that gravity travels in waves similar to those of electromagnetism. The General Theory of Relativity also ushered in an entirely new concept of the nature of the universe and the way it behaves. It was to do for the twentieth century what Newton's work had done for the seventeenth.

Actually it was in 1907, at the age of twenty-eight, that Einstein began digging at the roots of Newtonian mechanics. This re-examination of the fundamental premises of classical physics was prompted by Einstein's earlier work. Barely two years before, while a clerk in a Swiss pat-

It takes tremendous gravity-defying power in their lifting fans to make possible the V/STOL (Vertical Short Takeoff and Landing) aircraft. This one can take off from a confined area, then convert into a 500-mile-an-hour jet.



ent office, the German-born mathematician had established an international reputation with the publication of a brief *Special Theory of Relativity*. The revolutionary theory, which was to lead ultimately to the liberation of atomic energy, introduced several profound ideas which differed markedly from those proposed by Newton.

Einstein was struck by an odd coincidence. Keeping in mind that the gravitational force acting on falling bodies is proportional to their mass (or stated another way, bodies of different mass are accelerated equally by gravity), Einstein recalled that another type of force existed which, like gravity, is also proportional to the mass of the body it acted upon. The *inertial force,* as it was called by Newton, is produced by acceleration. A simple illustration will help make this important point clear.

Imagine yourself riding smoothly in a train. It's so smooth, in fact, that if you didn't have the shades pulled up you couldn't tell if you were moving or not! You lean over in your seat to engage the passenger in front of you in conversation. All of a sudden the train speeds up—accelerates—rapidly and you are thrown back against your seat. And if you keep your eyes open you will see that the other passengers, whether of large or small mass, are all jolted back at *exactly the same rate of speed as you.* The inertial force produced due to the train's acceleration has obviously acted upon each of you in strength directly proportional to your mass.

Consideration of this remarkable relationship between gravitational and inertial forces led Einstein to a conclusion of crucial importance. He formulated his findings in 1911 in his *Principle of Equivalence of Gravitational and Inertial Forces.* In effect, it simply states that there is no way to distinguish between acceleration and the effects of gravity.

It was this principle of equivalence that became the cornerstone of Einstein's General Theory of Relativity, which he was to spend the next five years developing, weaving a universe of "four-dimensional curved space."

A Hint of the World of Relativity

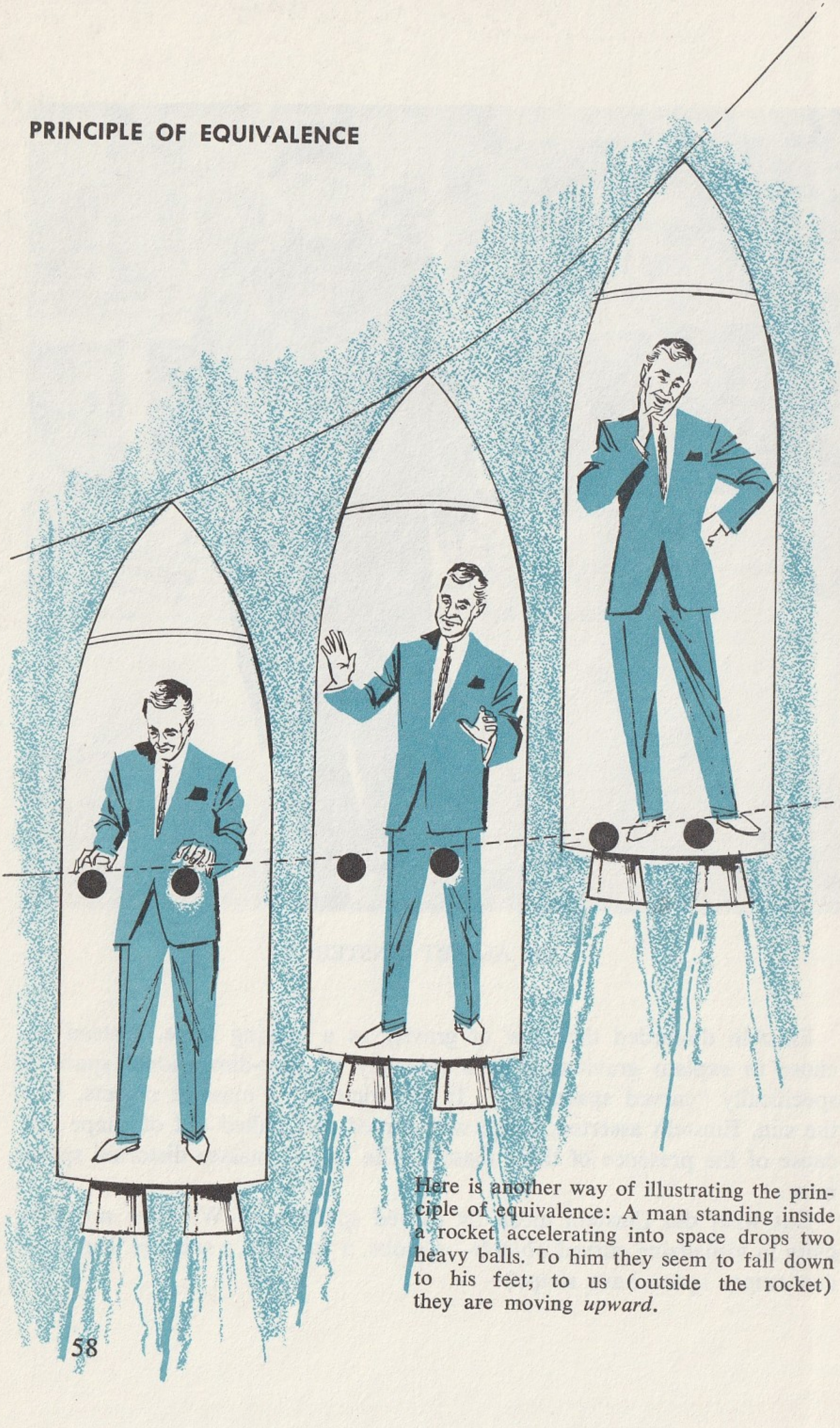
ONE OF EINSTEIN'S BIOGRAPHERS wrote an apology before he attempted to describe the General Theory without using mathematics. He wrote, in effect, that trying to explain the General Theory nonmathematically is like trying to play Beethoven's Ninth Symphony with only a saxophone. Not a very encouraging thought, but take heart. It is possible to get at least a hint of the elegant and profound world of relativity.

DR. ALBERT EINSTEIN

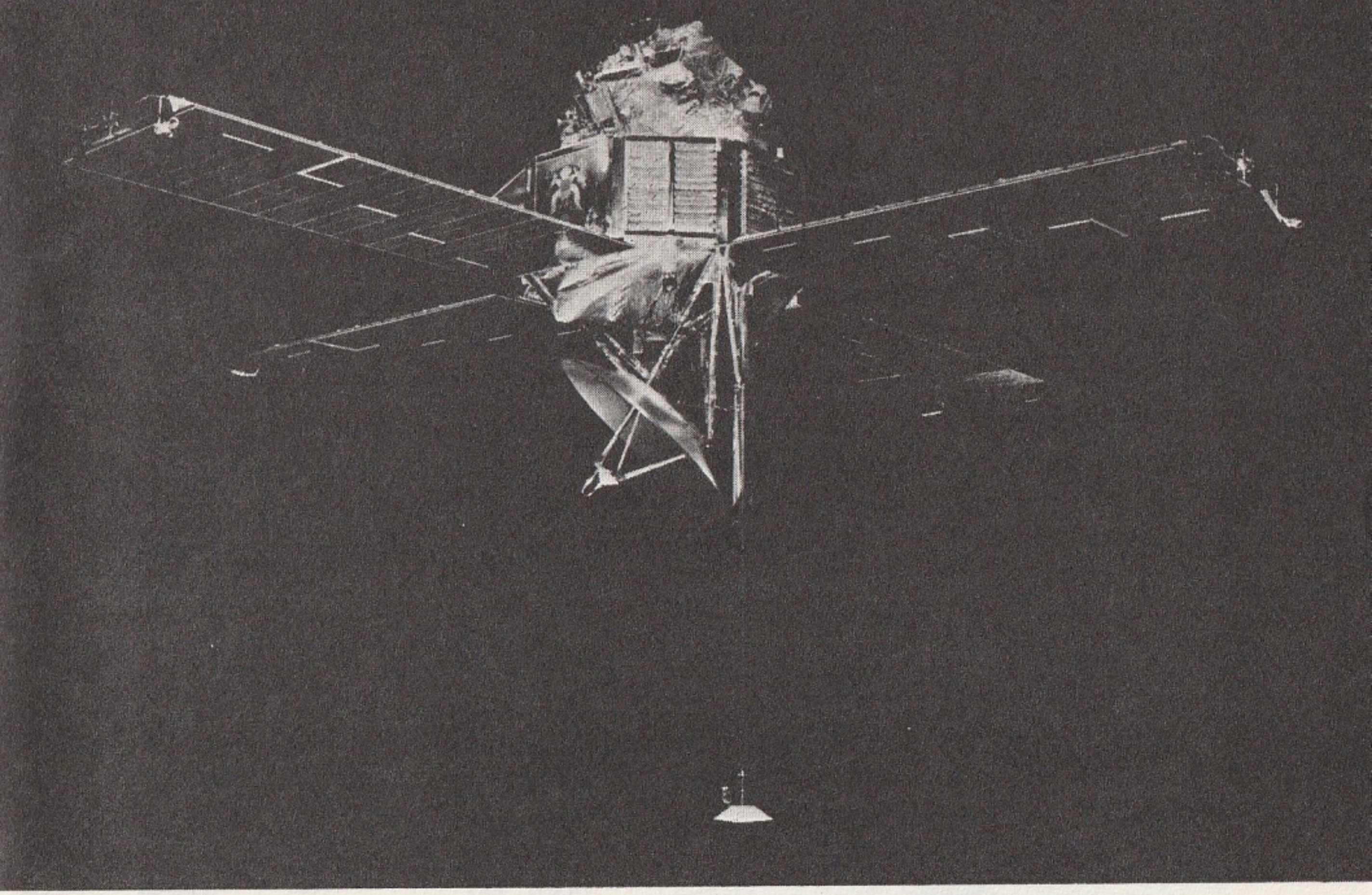
Einstein discarded the view of gravity as a tugging force. Instead he chose to explain gravitation as a property of four-dimensional space—specifically "curved space-time". In the vicinity of massive objects, like the sun, Einstein asserted, space was curved and pulled out of shape because of the presence of these masses. The largest masses distorted space most.

But what did Einstein mean by curved space-time? We have no difficulty in visualizing curved *objects*—a globe, a football, a sausage. But how can *empty* space have shape?

PRINCIPLE OF EQUIVALENCE



Here is another way of illustrating the principle of equivalence: A man standing inside a rocket accelerating into space drops two heavy balls. To him they seem to fall down to his feet; to us (outside the rocket) they are moving *upward*.



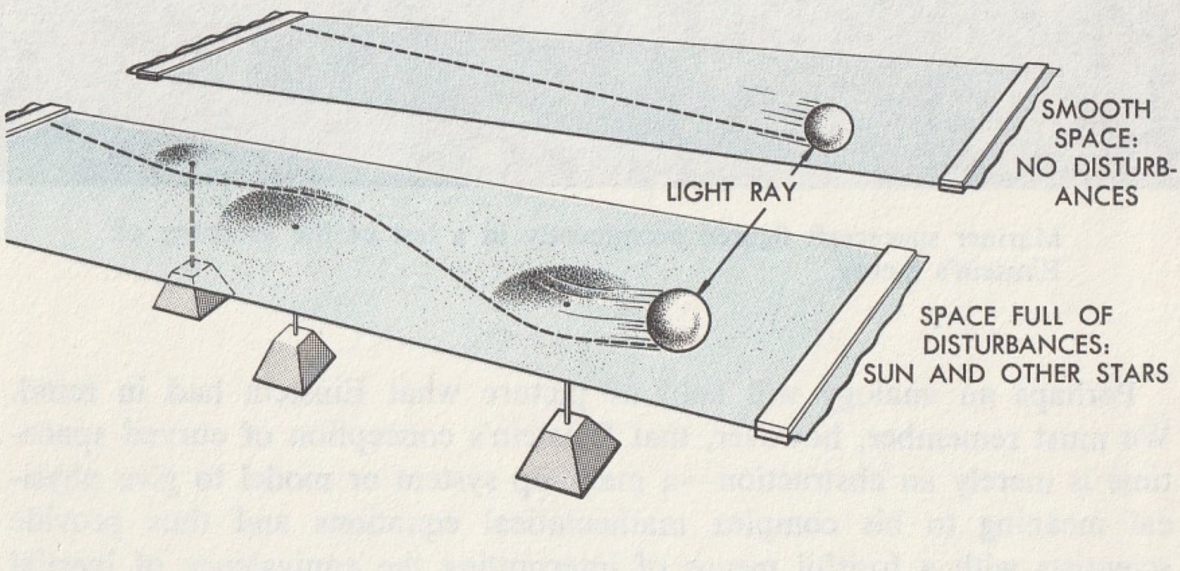
Mariner spacecraft figured prominently in a test of the accuracy of Einstein's theory.

Perhaps an analogy will help us picture what Einstein had in mind. We must remember, however, that Einstein's conception of curved space-time is merely an abstraction—a made-up system or model to give physical meaning to his complex mathematical equations and thus provide scientists with a fruitful means of interpreting the equivalence of inertial and gravitational "forces".

Suppose we stretch a long sheet of rubber until it is very taut and flat. We might do this over a large hollow bowl. The sheet represents empty space. Now let us roll a marble over the sheet. We shall consider the marble to represent a beam of light coming from a distant star. According to general relativity, light, which had been shown to be made up of very tiny bundles of mass, will be deflected by large masses. But at the moment there are no masses present in our model of the universe to produce ripples or distortions. So the marble traverses the sheet in a straight line as would light through "unkindled" space.

Now let us "dimple" space by hanging some lead weights from various points along the sheet. Where space had once been smooth, we now find many slopes and hollows. These hills and dales correspond to distortions

produced by large gravitational masses—the sun, planets, stars—represented by the lead weights. In the region where there are no weights, space is comparatively smooth and flat. Suppose we now roll our marble across this obstacle course. 'The "light beam" from the distant star bends toward the "sun", dipping into the slope produced by the sun's mass. The light beam would not be trapped by the sun's gravitational field, but merely bent slightly, because of its enormous speed. But if our marble were to represent the earth or some other planet, it is possible that in trying to follow the most nearly straight path it would continue to ride around the rim of the sun's hollow. Our model would then demonstrate planetary orbits.



It should be stressed at this point that in the presence of a gravitational field, for example, the distortions produced by the sun, celestial bodies such as planets and satellites, and even beams of light, will travel the straightest path available in curved space-time. Just as on the surface of the earth anyone moving along the straightest route available will pursue a great circle and eventually return to the point from which he began, so we can picture the circuits of the planets about the sun, and of the moons around their planets, as the most nearly straight paths possible in curved four-dimensional space. This path, the shortest route, is called a *geodesic*.

Was Einstein Correct?

EINSTEIN'S THEORY was so "far out" in every sense—including the literal one—that until the advent of powerful radio telescopes and space probes it was very difficult to judge with true precision the correctness of the theory that light, radio and electromagnetic waves are deflected by gravitational fields in space. In 1970, the results of two interesting experiments were announced, both supporting Einstein and putting down many of his doubters.

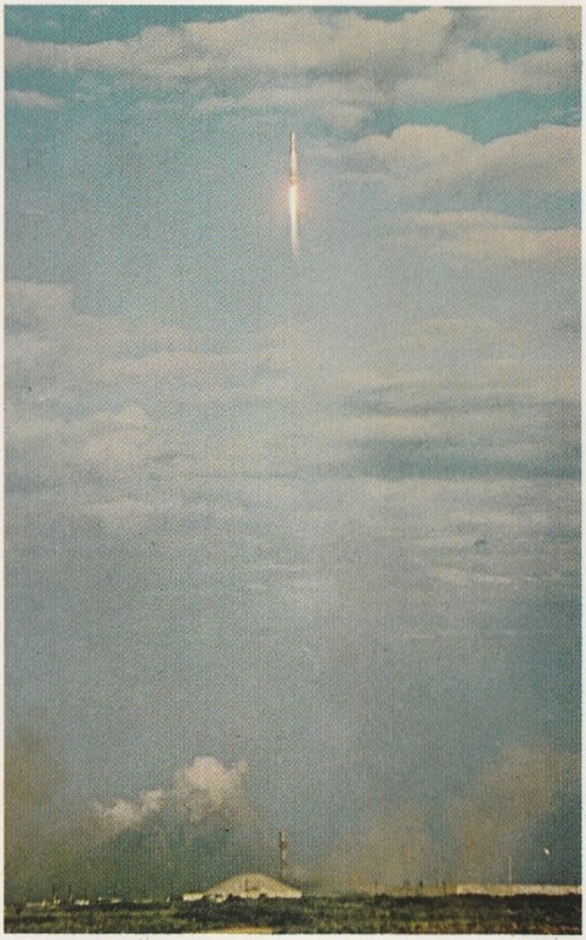
In June of that year astronomers at the California Institute of Technology reported using for the first time dish-shaped radio antennas up to 210 feet in diameter to check whether, as Einstein maintained, objects warp in space.

The Caltech scientists focused on two quasars (quasi-stellar radio sources) that emit powerful signals. As one quasar moved behind the sun they measured its radioed position in relation to that of the second quasar, whose signals weren't close enough to the sun to be deflected by the sun's field. The deflection of the signal of the quasar closest to the sun was tiny: 1.75 seconds of arc—about the width of a dime as seen from a mile away. But that figure was amazingly close to what Einstein predicted it should be: 1.77 seconds of arc.

Since 1919 astronomers have used optical telescopes to look for light waves from stars to the "bent" as they pass near the sun. Optical measurements, however, contain a twenty per cent uncertainty. Radio telescopes are far more precise and for that reason have given scientists more assurance of the accuracy of Einstein's theory.

In November, 1970, still another interesting test: The signals from two Mariner spacecraft were checked as they passed through the sun's field. The signals slowed slightly, as Einstein said they should. The Jet Propulsion Laboratory in California, using equipment precise to a millionth of a second, timed signals sent from earth and radioed back as the Mariners were on the far side of the sun. The measurements indicated a maximum delay of 204 millionths of a second for Mariner 6, as compared with an expected 200 millionths of a second using Einstein's theory. If the Newtonian theory had been the yardstick, there should have been no delay at all.

The space experiments actually represent a fourth type of test of the General Theory, all of which have borne Einstein out. The previous three types: measuring a frequency shift in the spectral line of red light from massive stars; measuring with optical telescopes the bending



One of the most powerful gravity-countering machines made by man—a space rocket—climbs into the sky over Cape Kennedy.

12. A TITAN ROARS ALOFT

of star light by the sun's gravity; and analysis of slight changes in Mercury's orbit around the sun.

Must It Be Newton vs. Einstein?

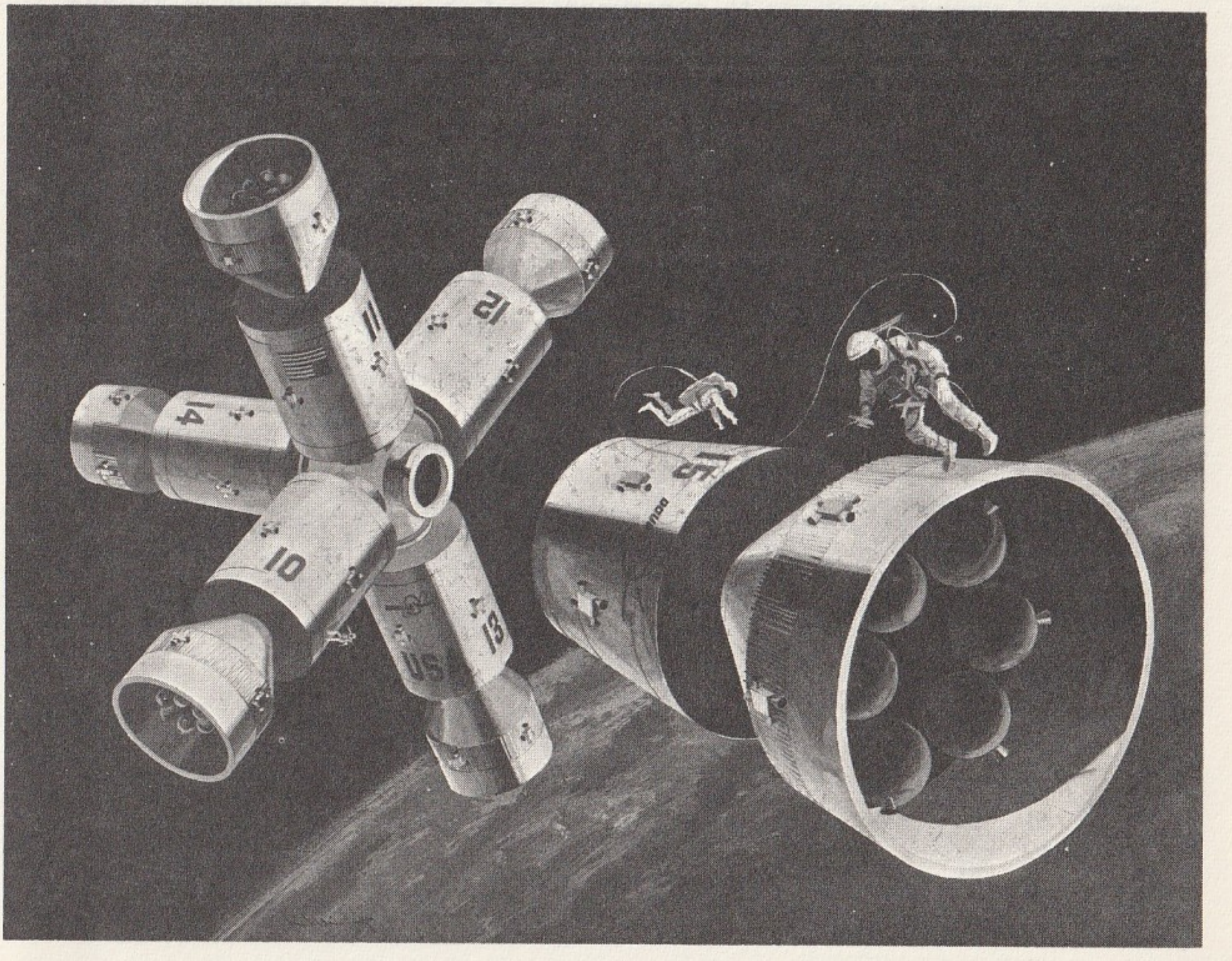
DID EINSTEIN dispose of classical physics and relegate it to the history books? Nothing could be further from the truth. Einstein showed that the Newtonian view was only an approximation of reality. But as it turns out, it proves to be a remarkably close approximation and so continues to be of fundamental importance to the world of science.

To review: Newton said that any two objects attract each other with a force depending on their mass and distance from each other. Einstein said that gravity is not a force but, in effect, the shape of space itself—and that massive objects warp space. The "bending" that is

observed when light waves or radio waves pass near the sun is simply the wave taking the shortest path through the space warped by a massive object.

In the service of scientists, Newton's mechanics still explain the motion of planets, the moon, artificial satellites, interplanetary space vehicles, tides, airplanes, automobiles—in fact any kind of motion in which the relativistic increases in mass do not become important. They do become important, as Einstein showed in his Special Theory of Relativity, when the speed of light is approached. But we no more need to worry about relativity when considering orbital velocities than a snail needs to worry about air friction! The earth plods along on its orbit at a speed of eighteen miles per second—one ten-thousandth the speed of light. Here Newton's physics works just fine. And even when the speed of light is approached, suitable corrections can easily be made in Newton's laws to compensate for relativity effects.

Space stations of the future will simulate earthlike gravity conditions, to enable crews, while inside, to work more efficiently.



Where Einstein's theory becomes vital is in considerations of the galaxies and cosmology in general. Scientists look to Einstein's equations to help with questions involving the size and shape of the universe as a whole, the sort of objects in it, and its history. With new tools becoming available, general relativity may someday enable us to understand the structure of the universe in its entirety.

The Mystery Remains

MEANWHILE, THE ESSENTIAL MYSTERY of gravity remains. In recent years some respected scientists believe they have located the source of the gravity waves that permeate the universe at a distance of 150,000 trillion miles—at the very center of the Milky Way, in a concentrated area of 10 billion suns. Others are not so sure. In any case, all ask: What causes the waves? Is it stars in the making? Perhaps worn-out, collapsing stars? How is so much energy produced eon after eon without consuming all the matter thought to be present in the universe?

No one knows for certain, and only the very brave will even venture a guess. Still, in thousands of laboratories around the world, dedicated men and women continue to experiment and theorize, hopeful of solving the riddle.

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